CONTROLLING LOCOMOTIVE EMISSIONS IN CALIFORNIA
Technology, Cost-Effectiveness, and Regulatory Strategy

REVISED FINAL REPORT

Report under ARB Contract Nos.
A032-169 and 92-917

submitted to
State of California
Air Resources Board
P.O. Box 2815
Sacramento, CA 95812

March 29, 1995

submitted by

Christopher S. Weaver, P.E.
Douglas B. McGregor

Engine, Fuel, and Emissions Engineering, Inc.
9812 Old Winery Place, Suite 22
Sacramento, CA 95827-1732
(916) 368-4770

This page intentionally left blank.

ABSTRACT

The objectives of this study were:

1. to identify a set of *feasible*† and *cost-effective* techniques to reduce locomotive pollutant emissions in California to the greatest extent possible at an acceptable cost;

2. to characterize the technical requirements, costs, emissions impacts, and impact on railway operations of each technique in sufficient detail to serve as a basis for regulation;

3. to identify and recommend areas where ARB or other public funding for additional research, development, and demonstration of specific techniques is required in order to make them available for widespread application; and

4. to develop and recommend a *regulatory strategy* and implementation schedule for reducing locomotive emissions in California as quickly and cost-effectively as possible, and estimate the emission benefit which would result.

Feasible and cost-effective control techniques for locomotive emissions include retarding injection timing and other engine modifications, selective catalytic reduction (SCR), use of liquified natural gas (LNG) fuel with low-emission dual-fuel or spark-ignition (SI) natural gas engines, LNG combined with SCR, and electrification. Use of a combination of dual-fuel and SI LNG engines could reduce locomotive emissions 80%, at a cost of less than $1,000 per ton of NOx eliminated. SCR added to diesel and LNG could produce NOx emission reductions of 90 and 97%, respectively, at costs less than $3,000 per ton. All of these technologies could be retrofit to existing diesel locomotives.

† A dictionary definition of feasible is *"capable of being done, possible"*. In this study we interpret "feasible" to mean it is not necessary that an emission control technology be demonstrated in railroad service in order to be judged feasible. A technology that has been proven in similar applications, or in limited testing, and which shows promise of working well in railroad service is considered feasible by this definition.

Electrification of all California line-haul locomotive operations with LNG+SCR in switch and local units represents the greatest potential emission reduction, 98%, but the cost would be ten times that of the next best (in terms of cost-effectiveness) option, with only a small NOx emission improvement. Based on these results, a regulatory framework has been proposed. This framework, based on an emissions "bubble", would reduce allowable locomotive emissions per net ton-mile transported by 80% between 1998 and 2005. Further R&D is required to develop an appropriate emission test procedure, to develop and demonstrate low-emission dual-fuel retrofit systems for locomotives, and to demonstrate the use of SCR retrofit systems.

In their comments on an earlier version of this report, the railroads have stated that the cost estimates developed herein are too low, and that the characterization of LNG and SCR use as technically feasible in railroads is too optimistic. Recalculation of the cost-effectiveness estimates using the railroad's data results in higher costs per ton overall, but these costs are still well within the range considered acceptable by ARB and SCAQMD. The data submitted also show that present railroad activity levels are much higher (in some cases, double) than those calculated from the 1987 inventory data, suggesting that actual railroad emissions may also be much higher than presently estimated. It is recommended that the ARB investigate present activity and emissions levels in greater detail.

CONTENTS

This page intentionally left blank.

LIST OF FIGURES

This page intentionally left blank.

LIST OF TABLES

This page intentionally left blank.

1. SUMMARY

This document is the revised final report of a study of locomotive emission control carried out by Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) under California Air Resources Board (ARB) Contract Nos. A032-169 and 92-917. The objectives of EF&EE's study were:

1. to identify a set of *feasible* and *cost-effective* techniques to reduce locomotive emissions in California to the greatest extent possible at an acceptable cost;

2. to characterize the technical requirements, costs, emission impacts, and impact on railway operations of each technique in sufficient detail to serve as a basis for regulation;

3. to identify and recommend areas where the ARB or other public funding for additional research, development, and demonstration of specific techniques are required in order to make them available for widespread application; and

4. to develop and recommend a *regulatory strategy* and implementation schedule for reducing locomotive emissions in California as quickly and cost-effectively as possible, and estimate the emission benefits which would result.

This study began in June, 1991, with a study kick-off meeting taking place in August, 1991. A preliminary report, documenting the results of our initial screening analysis of locomotive emission control technologies, was submitted to the ARB in November, 1991, and released for public comment in January, 1992. Comments from the rail industry were received and discussed at a meeting held in March of that year. In August, EF&EE submitted to the ARB a proposed regulatory framework for locomotive emission control. After review by the ARB, this framework was sent out for public comment. A public workshop to discuss the proposed regulatory framework was held December 16, 1992, and written comments in response to that workshop were received in January, 1993. A draft final report was submitted to the ARB for review in April, 1993; and a final report incorporating the ARB comments was produced in October. A public workshop to discuss the draft final report and ARB's plans for regulating locomotive emissions was held February 16th, 1994.

The bulk of the report was written in 1992 and 1993, which means the reader may find some pieces of information dated. This revised final report incorporates some limited changes in response to the comments received at the February 16th, 1994 workshop, and in subsequent written submissions. A summary of these comments, and our response to them, is given in Appendix C. The written comments themselves are reproduced in Appendix E (a separate volume, *Controlling Locomotive Emissions in California: Industry Comments*, available from the California Air Resources Board). Where appropriate, references to *Industry Comments* (except for the September 12, 1994 submission by EMA, which was too late for consideration) are included in the text of this report, and in the notes that appear in Appendix D. References to notes in Appendix D are denoted by superscripted numbers (for example, "[1]"). Footnotes are denoted with the symbol "†".

The remainder of this chapter summarizes the major results and conclusions of EF&EE's study. More detailed information and supporting analyses are provided in the chapters that follow. A guide to acronyms and definition of terms used in this report appears in Appendix B.

1.1 Locomotive Types and Technology

Nearly all railway locomotives used in the U.S. have diesel-electric drive systems. A large diesel engine (typically 2000-4400 horsepower) in the locomotive drives an electric generator, which supplies electric power to separate traction motors geared to each axle. There is no direct mechanical connection between the engine and the wheels; instead, the combination of electric generator and electric traction motors acts as an infinitely variable transmis-

Table 1: Locomotive emissions compared to U.S. Federal and California emission standards for heavy-duty vehicle engines.

	HD Emissions (g/BHP-hr)[a]				
	THC	NMHC	NOx	CO	PM
1991 Federal/Calif.	1.30	NR	5.0	15.5	0.25
1994 Federal (1993 Bus)	1.30	NR	5.0	15.5	0.10
1994 Bus	1.30	NR	5.0	15.5	0.05
1994 California	1.30[b]	1.20[b]	5.0	15.5	0.10
1996 California Off-Road	1.0	NR	6.9	8.5	0.4
	Locomotive Emissions (g/BHP-hr)[c]				
EMD 12-645E3B	0.33	NM	11.7	0.80	0.28
EMD 12-710G3A[d]	0.30	NM	11.6	0.90	0.20
GE 12-7FDL	0.60	NM	10.7	2.24	0.26

NR: not regulated
NM: not measured
[a] Transient duty cycle
[b] Manufacturers may choose to comply with either THC or NMHC standards.
[c] Source: Association of American Railroads, 1990 (Full-mode steady-state cycle).
[d] Source: Fritz, 1992; AAR 3-mode composite duty cycle.

sion. To slow down, the traction motors can be reversed to serve as generators, with the electric power so generated being dissipated in resistance heating grids on the top of the locomotive. This mode of operation is called "dynamic brake".

Standard locomotive control systems provide for eight discrete power settings or "notches" in addition to idle and dynamic brake. Each notch corresponds to a specified engine power output and RPM; to change power output, the engineer switches from one notch to another, but within a given notch, the engine runs essentially in steady state. Unlike truck engines, locomotive diesel engines do not experience rapid transient changes in speed and power output. This fact greatly simplifies the design of emission control systems for these engines.

Emissions from locomotives, like those from other heavy-duty diesel engines, are dominated by NOx and SOx. Table 1 compares brake-specific emissions for three current locomotive engines to the ARB emission standards for engines used in heavy-duty trucks and off-road equipment. NOx emissions, in particular, are very high compared to the emission standards set for other engine types by the ARB. SOx emissions are determined by the sulfur content of the fuel, and may also be very high compared to other engines, as locomotive fuel is presently exempt from the sulfur limit of 0.05% by weight for diesel fuel used by road vehicles and off-highway equipment (however, it will not remain exempt, and therefore we have chosen not to include SOx emissions in Table 1). Emissions of diesel particulate matter (PM) are less for locomotives than for uncontrolled diesel engines in on-road vehicles. This is because PM emissions tend to be much worse on engines subject to transient changes in load and speed, and locomotive engines tend to experience more steady-state operation than truck engines. In addition, locomotive engine manufacturers have made conscientious efforts over the years to control visible smoke emissions, and this helps to limit the soot component of the PM emissions as well.

1.2 Importance of Locomotive Emissions

Emissions from railway locomotives are estimated to contribute significantly to total NOx and SOx inventories in the air basins of California[1]. Emissions of hydrocarbons, diesel particulate matter, and toxic air contaminants by locomotives - although small in relation to the total inventory - may produce significant local impacts. In a previous study carried out for the ARB (Booz-Allen, 1991) railway locomotives were estimated to have emitted some 99 tons of NOx, 7.3 tons of SO_2, 2.2 tons of diesel particulate matter, and 4.2 tons of reactive hydrocarbon emissions per day in the South Coast, Bay Area, San Diego, Sacramento, San Joaquin, and Central Coast air basins in 1987. These values amounted to 3.4% of the total NOx, and 1.6% of total estimated SO_2 emissions, but only .12% of total HC and .06% of total estimated PM10 emissions in these air basins, respectively. In the Sacramento Valley air basin, one of the most heavily impacted, locomotives accounted for 8.6% of estimated total NOx emissions in 1987. In the South Coast Air

Basin, which has the highest ozone and NO_2 levels in the U.S., locomotives produced 2.6% of the 1987 NOx inventory. For comparison, heavy-duty diesel trucks accounted for 12.5% of the 1987 inventory in the South Coast, while ships accounted for 2.8%.

Table 2: 1987 emissions from locomotives in six air basins of concern in California (Booz-Allen, 1991).

	Annual Emissions (tons)				
	HC	CO	NOx	SOx	PM
Mixed Freight	551	1,770	13,627	1,008	297
Intermodal Freight	412	1,344	10,163	745	221
Passenger Trains	35	81	1,183	110	26
Subtotal, All Line Haul	998	3,195	24,973	1,863	544
Local Trains	351	1,117	7,774	580	167
Yard Operations	201	504	3,441	187	78
Total	1,550	4,816	36,188	2,630	789

Table 2 summarizes total 1987 locomotive emissions in air basins in California, as estimated by the Booz-Allen study. As this table shows, line-haul freight operations accounted for nearly two-thirds of total emissions in the air basins, switcher operations for about 10%, and passenger operations for about 3% of total emissions, with the rest being due to local train movements. Line-haul freight emissions are split more-or-less evenly between intermodal (long-distance carriage of truck trailers and/or shipping containers on specialized cars) and traditional "mixed" freight trains of boxcars, gondolas, flatcars, and so forth.

Quantitative data on locomotive emission trends since 1987 are not available, but a qualitative evaluation suggests that emissions today are probably higher than the 1987 value. Although the tonnage of freight shipped by rail has increased significantly since 1987, nationwide fuel consumption by railroads has declined somewhat, and fuel-efficiency (measured as ton-miles per gallon of fuel) has improved. In addition, the engines used in new locomotives now coming into service have lower brake-specific emissions than those they are replacing. On the other hand, data on current railroad activity levels in California, submitted as part of the Southern Pacific's comments on our previous report, show activity levels in Southern California that are more than double those we calculated from the 1987 inventory data. Thus, total emissions from freight transport in Southern California may have increased significantly. In addition, the increasing popularity of commuter trains (e.g. L.A. MetroLink) and interurban passenger trains (e.g., Amtrak *Capitols*) will have led to increased emission from passenger service. Given the rapid changes in the rail industry, it is important that the ARB update its locomotive emissions inventory on a regular basis.

Although locomotive emissions make up only a small percentage of the total emission inventory in most California air basins, the pollution control requirements for air quality attainment in the South Coast (and, to a lesser extent, in other air basins of concern) are such that their contribution is still significant. Strict emission regulations have already been adopted for most stationary sources of NOx and SOx, as well as cars, heavy-duty trucks, and many off-highway mobile sources (including, but not limited to, the following applications: agricultural tractors, backhoes, excavators, dozers, log skidders, trenchers, motor graders, portable generators, and portable compressors) (California Air Resources Board, 1993a). Present NOx emission limits for new heavy-duty truck engines are less than half the level from uncontrolled truck engines, and new regulations being developed by the ARB would cut this level in half again, to 2.5 g/BHP-hr or less. Along with ships, locomotives presently constitute one of the largest classes of *uncontrolled* NOx and SOx sources. In order to achieve State and Federal standards for ambient ozone concentrations, the South Coast Air Quality Management District (SCAQMD) estimates that NOx emission in 2010 will have to be reduced by 69% from the 1987 level. If locomotive emissions continued at the 1987 level, they would constitute more than 8% of the total NOx inventory by 2010.

1.3 Locomotive Emission Control Technologies

The results of EF&EE's study show that substantial control of emissions from locomotives is possible at moderate cost. Emission control measures investigated by EF&EE included[2]:

- changes in diesel fuel composition;
- improvements in operating efficiency to reduce fuel consumption;
- modifications to existing diesel engines to reduce their emissions;
- replacement and rebuilding of diesel locomotives with lower-emitting engine designs;
- alternative fuels (methanol and natural gas);
- retrofitting selective catalytic reduction (SCR) to existing diesel locomotives;
- a combination of natural gas plus SCR; and
- electrification of line-haul operations.

Electrification of local and switcher operations was not considered, due to the enormous additional costs of electrifying local rail lines and switcher track.

Table 3 shows the NOx reduction calculated to be achievable from line-haul locomotives, using each of the technical approaches evaluated. Improvements in operating efficiency (discussed in Chapter 5) are not included. These improvements have likely already occurred, to the extent possible, assuming that the increase in rail traffic since 1987 has been accomplished with no change in emissions. Table 3 also shows the estimated cost and average cost-effectiveness of applying each technological option to the entire California line-haul locomotive fleet. The annualized costs of establishing and maintaining the

Table 3: Summary of costs and NOx reductions, line-haul locomotives.

	Baseline NOx (tons/yr):	24,973		
	NOx Reduction (tons/yr)	**Percent Reduction**	**Cost (MM $/yr)**	**Cost-Eff. ($/ton)**
Rebuild/Replace	N/A	N/A	N/A	N/A
LNG Dual Fuel	19,551	78%	$18	918
LNG SI	21,722	87%	$31	1,439
LNG + SCR	24,430	98%	$49	2,026
SCR	22,673	91%	$78	3,433
Engine mods	11,272	45%	$39	3,474
Low aromatic fuel	2,675	11%	$44	16,541
Electric	24,973	100%	$506	20,262

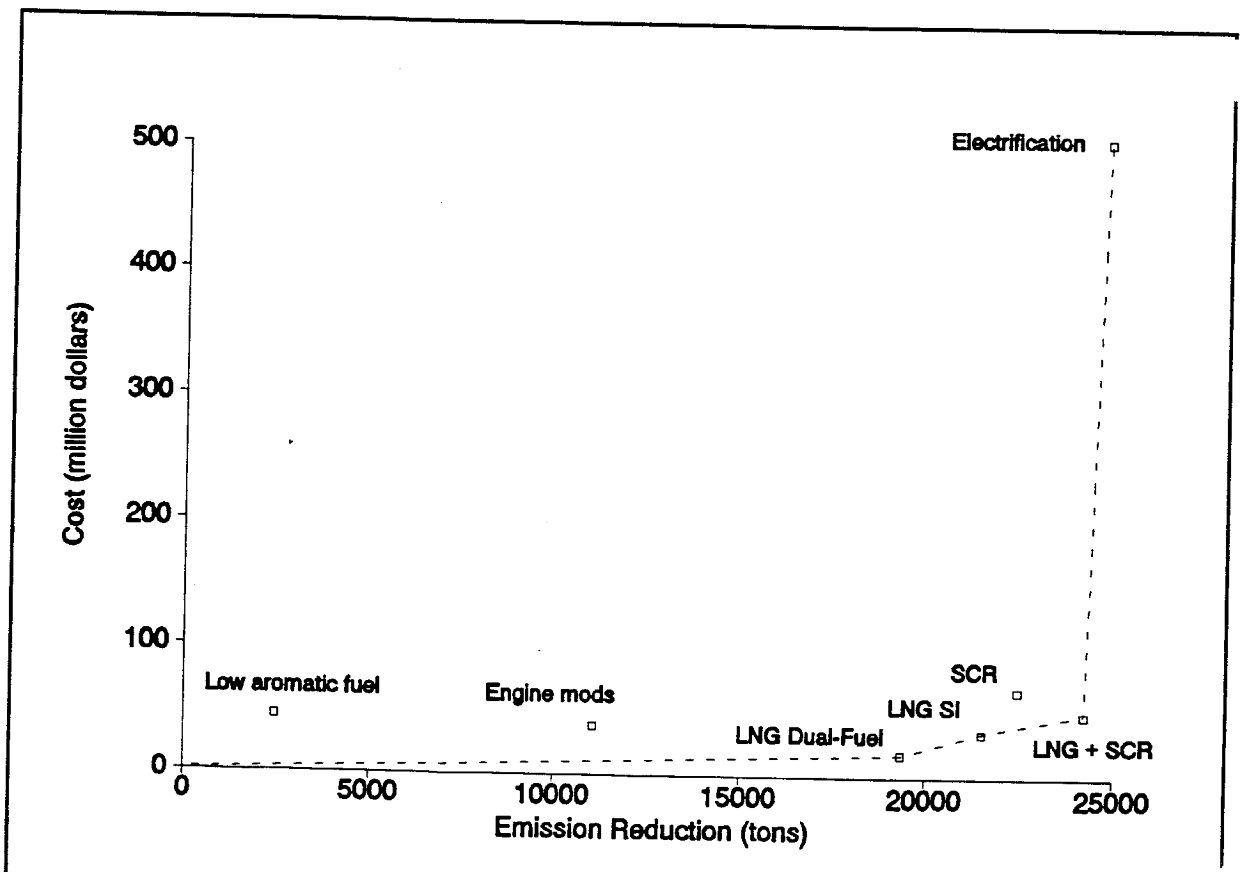

Figure 1: Cost vs. emission reduction for potential line-haul locomotive control measures.

California-only fleet - estimated in Chapter 4 at $24.4 million per year - are also included in the costs of each option.

Figure 1 is a plot of the cost of each reduction option versus the NOx emission reduction, in tons, attributable to that option. The *average* cost-effectiveness for each control measure is proportional to the slope of a line drawn between the corresponding point on the graph in Figure 1 and the origin (which itself represents the "do nothing" option). The slope value, called dollars per ton, was calculated by dividing the cost by the reduction in emission (annual tons of NOx).

As Table 3 shows, the estimated cost per ton for the LNG dual-fuel option is very low, and those for LNG SI, selective catalytic reduction (SCR), LNG+SCR, and engine modifications are all moderate. If, for some reason, LNG were not feasible, the cost-effectiveness of the SCR option alone (compared to the "do nothing" or "engine modifications" option) would also be attractive, as it could potentially eliminate 91% of the 1987 NOx emissions. Note that some measures, such as engine modifications, have good cost-effectiveness but provide only limited emission reductions. Although electrification of line-haul operations would give the largest NOx reduction, the incremental costs (the difference between two options) for a statewide system compared to the other options are very high, and the incremental emission benefits are only modest. In addition, we know that electrification will not actually give 100% reductions, since electric power generation results in some NOx, but we were unable to quantify these emissions. Nonetheless, it should be obvious that heavily travelled routes will be more cost-effective than lightly travelled routes, and further study would reveal which California routes would elicit the greatest cost-effectiveness. The combination of LNG plus SCR would give almost the same degree of emission reduction at much lower cost. This would also serve to establish the infrastructure required for possible natural gas fuel-cell locomotives in the future.

- continued on next page -

It is also desirable to look at the cost and emission reduction totals for local and switcher locomotives. The costs and emission from local and switching activities are combined together here, although in reality locals may resemble line-hauls, switchers, or both, depending on the railroad. The results are shown in Table 4 and Figure 2. As with the line-haul locomotives, dual-fuel shows the best cost-effectiveness of the emission control options for locals and switchers, with a cost per ton even less than that for line-haul locomotives. This is due to the absence of extra costs for changing power at California "gateways" (hypothetical facilities for chang-

Table 4: Summary of costs and NOx reductions, local and switcher locomotives.

	Baseline NOx (tons/yr):	11,214		
	NOx Reduction (tons/yr)	**Percent Reduction**	**Cost (MM $/yr)**	**Cost-Eff. ($/ton)**
Electric	N/A	N/A	N/A	N/A
LNG Dual Fuel	5,850	52%	$3	597
LNG SI	9,461	84%	$7	776
Engine mods	2,534	23%	$4	1,598
LNG + SCR	10,602	95%	$17	1,621
SCR	9,805	87%	$26	2,602
Rebuild/Replace	6,263	56%	$25	3,927
Low aromatic fuel	978	9%	$5	5,221

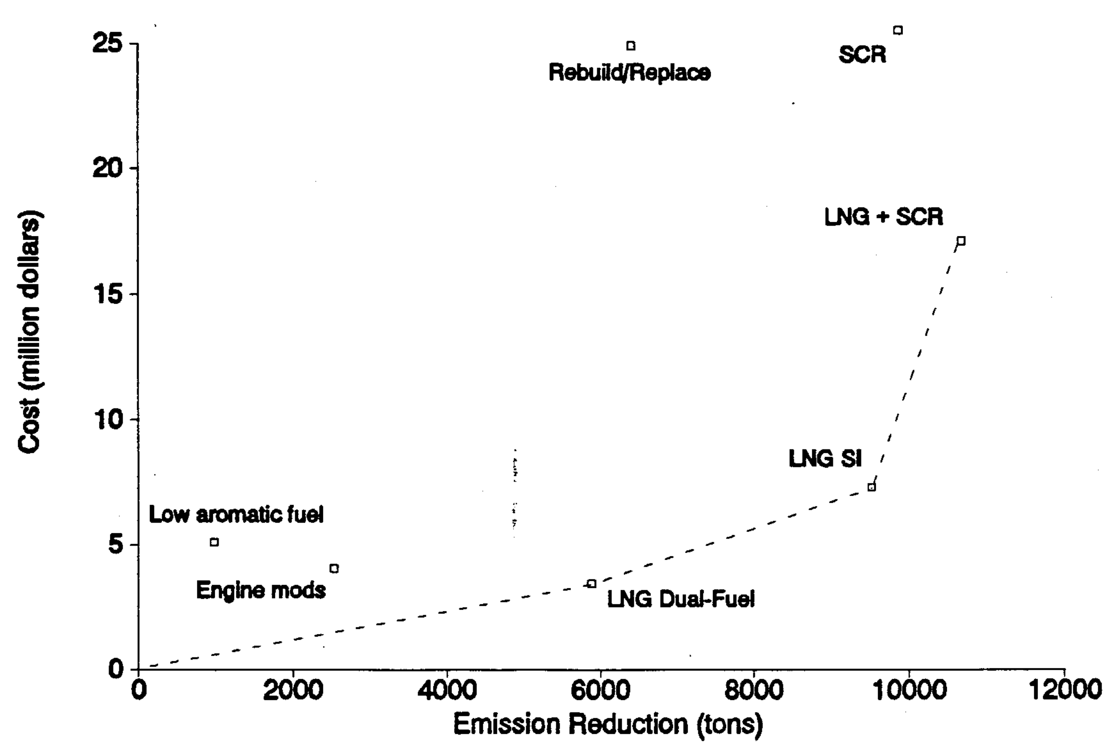

Figure 2: Cost vs. emission reduction for potential local and yard locomotive control measures.

ing from normal to low-emission locomotives). The emission reduction effectiveness of dual-fuel conversion is lower in switchers and locals, however, because of the predominance of idle and low-load operation. For switch and local locomotives, SI LNG engines give much better emission reduction, at a cost per ton only slightly higher than for LNG with dual-fuel engines. LNG+SCR gives the greatest total reductions, but its cost is high. We did not consider that electrification would affect switching or local emissions to any significant extent, as the cost of electrifying local branch lines and rail yards would be too high.

- continued on next page -

Since it would be desirable to reduce the emissions from line-haul, local and switcher locomotives together, at the least possible cost, they are combined in a third analysis. Table 5 was constructed by summing the relevant portions of Table 3 and Table 4 (and the results are shown graphically in Figure 3). There

Table 5: Summary of costs and NOx reductions, combined line-haul, local and switcher locomotives.

Baseline NOx (tons/yr): 36,188	NOx Reduction (tons/yr)	Percent Reduction	Cost (MM $/yr)	Cost-Eff. ($/ton)
LNG Dual Fuel	25,434	70%	$22	858
LNG Dual-Fuel Line-haul & LNG SI Locals/Switchers	29,074	80%	$26	882
LNG SI	31,245	86%	$43	1,376
R/R Locals-Switchers, Dual-fuel line-hauls	25,958	72%	$43	1,667
LNG + SCR	35,103	97%	$67	1,911
SCR	32,543	90%	$95	2,909
Engine mods	13,805	38%	$43	3,112
Low aromatic fuel	3,653	10%	$50	13,610
Electric line-hauls and LNG + SCR locals/switchers	35,645	98%	$524	14,688

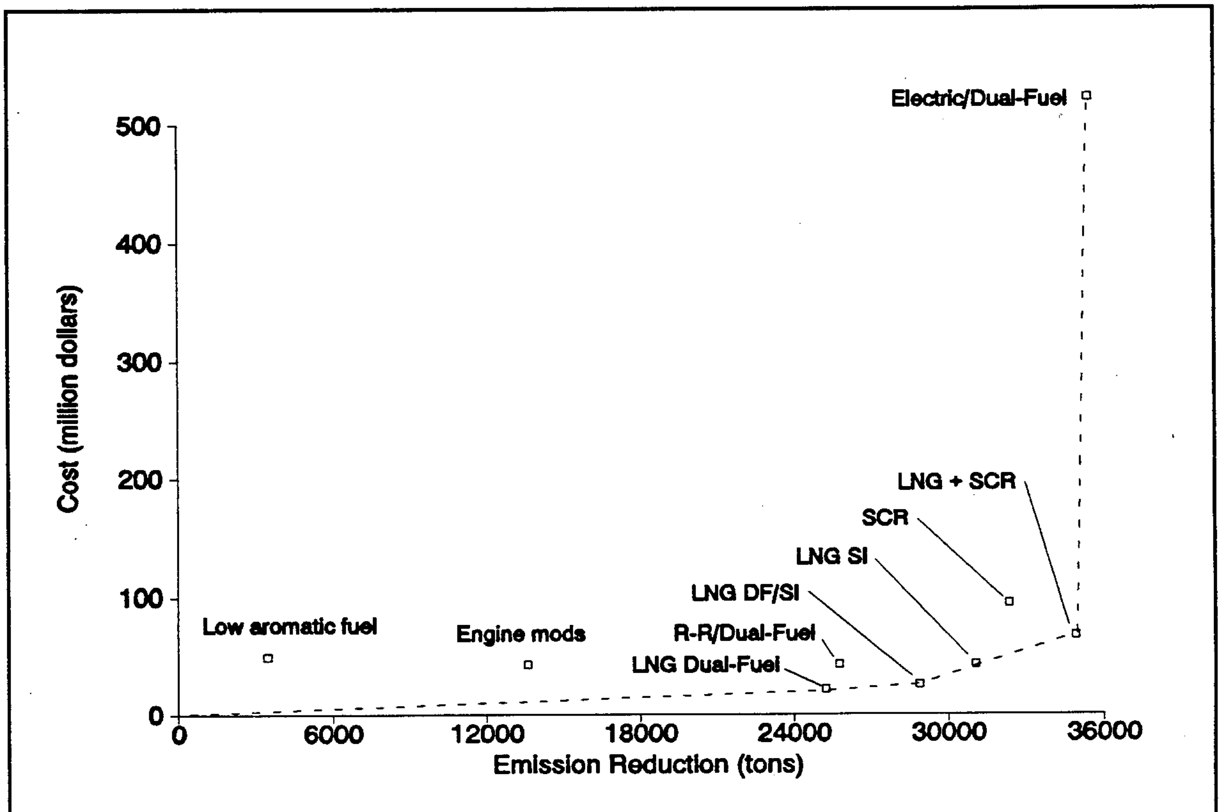

Figure 3: Cost vs. emission reduction for potential line-haul, local, and switcher locomotive control measures.

are many possible combinations, but only nine are highlighted here, to show the relative cost-effectiveness.

As Table 5 and Figure 3 show, the options for locomotive emission control with the best cost-effectiveness figures all involve the use of LNG. Converting existing diesels to dual-fuel operation could reduce emissions by 70% (more if advanced dual-fuel technologies allow a reduction in idle and light-load emission), at a cost less than $1,000 per ton. Use of low emission SI LNG engines in locals and switchers would increase the emission reduction to 80%, at an average cost-effectiveness $882 per ton. Use of SI engines in line-haul units as well, or the addition of SCR to the dual-fuel engines, would produce even larger emission reductions, but at significantly higher cost. Combining electrification of line-haul locomotives with dual-fuel+SCR in local and switch locomotives would produce the highest level of control efficiency - 98% - but the costs for a statewide electrified system are substantially higher.

Converting all locomotives to dual-fuel would appear to be the most cost-effective approach. Indeed, except for the costs of establishing and maintaining separate power in California, we estimate that this option would actually result in a small saving compared to the status quo. If, as now appears possible, use of LNG locomotives eventually becomes widespread, the need to maintain the separate California fleet would be reduced or eliminated, with a corresponding saving in cost. If, for some reason, LNG proved not to be feasible, SCR would also be a cost-effective choice to achieve substantial emission reductions at moderate cost. Regardless of how the various options are compared to one another, the table shows that all the options are cost-effective in removing oxides of nitrogen from the atmosphere.

1.4 Proposed Regulatory Strategy

The analysis of potential emission control measures summarized above shows that NOx emission could be reduced by 80% or more through the use of LNG locomotives, by 90% retrofitting SCR on diesel engines, and by 97% using natural gas plus SCR. The cost-effectiveness of these controls, at less than $3,000 per ton of NOx eliminated, is also extremely attractive compared to the costs of NOx control regulations that have been imposed on other sources (e.g., the SCAQMD guidelines of 25,000 dollars per ton for stationary NOx sources, and 20,000 dollars per ton for stationary VOC sources). The case for regulation of these emissions is thus very strong. Because of the importance and complexity of the railway industry, however, care and flexibility in the application of emission requirements are necessary. Emission regulations should be structured so as to avoid creating an incentive to shift from rail to other (possibly more polluting) modes, such as trucks. They should allow for future growth in rail transport, and should provide incentives for both technological and operational measures to reduce emissions, without entangling the ARB excessively in railway management. Based on these considerations, EF&EE proposed a regulatory structure which would establish basin-wide emission limits for each railroad, while leaving them free to satisfy the limits in the most cost-effective manner. A preliminary version of this proposal was discussed at a public workshop held December 16, 1992, and the proposal has been modified to reflect comments received at that workshop. The proposed regulatory framework includes the following elements:

- Basin-wide emission ceilings - Annual emission ceilings would be established for each railroad, including short lines, in each air basin of concern. The ceiling would be based on 1987 emissions multiplied by a reduction factor and by a factor reflecting changes in traffic volume. If a railroad's emissions were less than the ceiling, the difference could be banked for use in future years, or possibly (under a market-based control option) traded to other railroads or possibly to other mobile or stationary sources. Credits could be banked indefinitely. Excursion, historical, and other very small railroad operations would likely be exempt from the ceilings.

Table 6: Proposed emission phasedown schedule for locomotives.

Year	Allowable Emissions (% of growth-adjusted baseline)				
	NOx	PM	SOx	NMHC	CO
1998	90%	130%	17%	200%	200%
1999	80%	130%	17%	200%	200%
2000	70%	130%	17%	200%	200%
2001	60%	117%	17%	200%	200%
2002	50%	103%	17%	200%	200%
2003	40%	90%	17%	200%	200%
2004	30%	77%	17%	200%	200%
2005	20%	63%	17%	200%	200%
2006	20%	50%	17%	200%	200%
2007	20%	50%	17%	200%	200%
2008	20%	50%	17%	200%	200%
2009	20%	50%	17%	200%	200%
2010	20%	50%	17%	200%	200%
2011	20%	50%	17%	200%	200%
2012[a]	20%	50%	17%	200%	200%

[a] In addition, a research target of 90% NOx reduction would be established for 2012. This target would be reviewed in 2003.

- Emission baselines - For the major railroads and Amtrak, the 1987 emission and traffic volume baselines would be based on the Booz-Allen inventory study. For the short lines not included in the Booz-Allen study, emission estimates would be based on 1987 fuel consumption data and the best available data on emission factors (possibly including source tests). For new rail service not in effect in 1987, such as the L.A. Metrolink, an appropriate baseline would be developed based on similar operations.

- Emission reduction factors - Emission reduction factors would become more stringent over time, and would be uniform for all air basins of concern, unless the

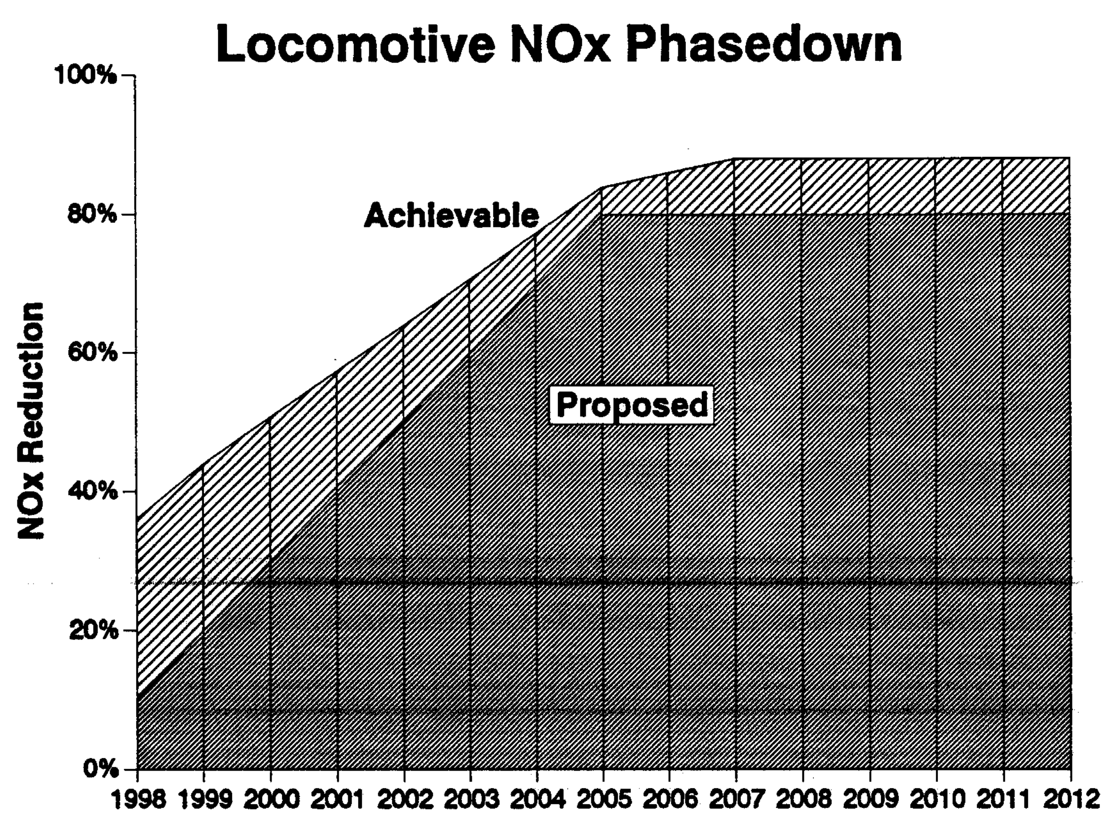

Figure 4: Proposed locomotive NOx phasedown schedule vs. technologically achievable reduction.

responsible air district showed that more stringent reductions were necessary and feasible. The proposed phasedown schedule is shown in Table 6. For NOx (the pollutant of greatest concern), allowable emissions would be phased down from 90% of the baseline in 1998 to 20% in 2005 and thereafter. Figure 4 compares the level of NOx reduction estimated to be technologically achievable (using the more cost-effective LNG approach) with the emission reduction proposed for each year. The proposed reductions are less than the level that could be achieved in the early years. This will allow the railroads to build up a bank of credits, providing a cushion against implementation problems, and helping to ensure orderly implementation of the control program.

- Traffic volume adjustments - The emission ceiling for each railroad would be a linear function of the traffic volume - doubling traffic volume would double the emission ceiling, and halving it would cut the emission ceiling in half as well. For freight, traffic volume adjustments would be based on net ton miles in each air basin. For Amtrak, the traffic volume adjustments would be based on passenger-miles carried, plus a further allowance for any freight (e.g. mail) carried by the train. Commuter rail lines would be treated separately from Amtrak intercity operations.

- Locomotive activity monitoring - Locomotive activity and emissions in each air basin would be monitored on an individual locomotive basis, in order to account for locomotives that are malfunctioning, high emitters, or otherwise different from average. Railroads would propose and implement their own monitoring systems, subject to the ARB approval and audit.

- Locomotive emission testing - Locomotive emissions of NOx, PM, CO, and VOC, and fuel consumption in each notch would be measured for every locomotive operating in the air basins of concern. Measurements would be made at 6-month intervals, or when engine mechanical work is carried out that could affect emissions, whichever is more frequent. Emission measurements could be carried out either by the railroads themselves, with appropriate regulatory oversight, or by a separate contractor. Testing is estimated to take about 1 hour per locomotive, using a suitable short test to be developed, and would be integrated into the regular periodic maintenance schedule. Some R&D will be required to develop a standard short test procedure.

1.5 Research, Development, and Demonstration Needs

One of EF&EE's tasks in this study was to identify key areas in which additional public funding is required for research and development (R&D). Based on the analysis given in the following chapters, we have identified three areas in which we recommend that the ARB, SCAQMD, and/or other public agencies support further R&D. These areas are the following:

1. Emission testing - R&D is needed to develop and standardize a suitable short test procedure for measurement of NOx, HC, CO, and PM emission and fuel consumption in locomotives. This procedure is needed to determine emission levels from individual locomotives in order to verify compliance with the proposed "bubble" emission limits. Development of this procedure is estimated to require about 1 year, at a cost of $200,000, plus $200,000 for equipment (one test site).

2. Selective catalytic reduction - Funding is required for a program to apply and demonstrate SCR in a line-haul locomotive. Such a demonstration is needed before SCR could be applied on a large scale. Development and demonstration are estimated to require about two years each, with total costs of around $1.9 to $2.1 million.

3. Low-emission dual-fuel engines - Funding is required to develop a low-emission dual-fuel conversion system for the EMD locomotive engine, and to demonstrate this engine in line-haul and local service. Development and demonstration would require about two years each, at a cost of around $3.0 million.

It is recommended that work on the emission test begin as soon as possible, as development of this test is on the critical path for implementation of the proposed "bubble" regulation in 1998. Development and award of requests for proposal (RFPs) for the two larger demonstration programs should also take place during 1995, with a goal of starting work at the beginning of 1996.

This page intentionally left blank.

2. RAILROADS IN CALIFORNIA

This section describes the different types of railroad operations, as well as the major rail lines operating in California, and describes the technical characteristics and operational environment of today's railroad systems.

2.1 Railroads and Commerce

Conventionally railroads are rated according to their financial size. A *Class III* railroad has annual revenues of up to $19.1 million. A *Class II* railroad has annual revenues of $19.2 to $96.0 million. A *Class I* railroad has annual revenues of $96.1 million or more. These are 1992 values; the ICC adjusts the levels for inflation annually.

The business of the railroad is transportation. Railroads excel at transporting large quantities of goods over long distances, typically point-to-point between major urban centers. Such *line-haul* transportation is the primary function of major railroads operating in California, which are Union Pacific Railroad Company, Southern Pacific Transportation Company, and Atchison, Topeka, & Santa Fe Railroad. To support these line-haul operations, railroads also require *local* trains to collect cars from and distribute cars to towns and industries outside the major rail termini, and *switching* operations to distribute and re-arrange cars within these termini. Increasingly, these local and switching operations are being turned over to smaller *short-line* railroads, which are able to operate them more profitably.

Among the commodities transported by rail are canned fruits and vegetables, grain mill products, beverages or flavoring extracts, sawmill products, paper, industrial chemicals, coal, crude oil, plastic materials, steel rolling mill products, and motor vehicles. A great variety of other products are also transported packed in truck-trailers or shipping containers. Shipments originate from and terminate at *shippers*, such as factories, production plants, or marine terminals, and are later picked up by railroads and assembled into trains. For example, a plant that makes refinery chemicals may own or lease tank cars in which it loads a week's production. Nearby, a ship may unload coils of steel from overseas and place them on flatcars. Still another plant may be filling tank cars with crude oil, which will be sent to refineries in another city. Eventually, often at the end of the week, the cars are picked up by a railroad. The largest shippers have their own locomotives and crews to move the company's cars (these are called "industrial" railroads). The small numbers and light duty cycles of industrial locomotives mean that their emissions are much less than those from Class I railroads. However, an industry with 4 locomotives could emit 64 tons of NOx per year - not an insignificant amount.

Line-haul operations - The major railroads are increasingly specializing in long-distance, point-to-point transportation. Where large quantities of goods must travel long distances, trains are by far the most efficient and economical transportation choice. Line-haul trains can be further subdivided, based on the type of lading, into *mixed freight*, *bulk*, and *intermodal* trains.

Mixed freights, as their name implies, consist of a mixture of different types of cars carrying different commodities, and may include boxcars, flatcars, tank cars, gondolas, and other specialized types. Individual cars and groups of cars are collected by local trains and brought to a central location, where they are *classified* (sorted) into groups bound for specific destinations. These groups are then assembled into a train, coupled to a locomotive *consist* (a group of locomotives, generally containing between two and six units), and pulled to their destination in another rail terminus such as Kansas City, Houston, or Chicago. Mixed freight trains are the most common trains in California. In 1987, California mixed train hauls amounted to 27 billion gross ton-miles (Booz-Allen, 1991).

Another important category of line-haul trains are bulk or unit trains. These trains are made up of many cars, all carrying the same commodity, typically from a single source to a single destination. Commodities typically transported by these trains include crude oil, grain products, and coal. Bulk trains are a very small part of California transport business, but they are profitable for railroads in other parts of the country because they do not compete with trucks in these markets. One example of a bulk train in California is the crude oil train from Bakersfield to Los Angeles.

Another and increasingly important category of line-haul trains is *intermodal*. Intermodal traffic accounts for some 22% of the US carloadings (*Railroad Facts*, 1992). These trains consist of two types of cars: flat cars which carry truck-trailers, and specially-designed cars which carry shipping containers - rectangular metal boxes that are designed to stack inside and on top of ships. These containers are also designed to be hauled by trucks, and this is why such traffic is so important to the railroads. The use of containers or truck-trailers in intermodal service allows shippers and recipients not located on rail lines to make convenient use of rail transport, and can also provide quicker and more reliable service than traditional mixed-freight operations. On western railcars, containers can be double-stacked (one on top of another) to maximize train utilization. The rapid growth in trailer-on-flat-car (TOFC), container-on-flat-car (COFC), and doublestack container service is largely responsible for the recent revival of rail transportation in California.

Following is the path of a typical container load: a ship arrives at the Port of Los Angeles with hundreds of containers. Most of these containers are bound for inland US terminals, some for Los Angeles and its environs, and some for European destinations. The containers are loaded onto trailer frames at the dock. From there, trucks haul the containers to the recipients (if they are local) or to the rail intermodal facility if they are bound for more distant destinations. There, the load is identified and removed from the trailer. The trailer is stored in an area separate from the container (to be re-mated later with outgoing containers), and the driver goes back for another load. Containers also originate locally, and are hauled by truck to the rail intermodal facility.

Once at the intermodal facility, the container is loaded on a special doublestack container car, along with other containers bound for the same destination. When a full train of these cars is loaded, it leaves for the eastern terminals, sometimes stopping enroute to pick up additional loaded cars from intermodal facilities along the way. When the train arrives at its destination, the loading process is reversed, and trucks deliver the loads to their local destinations. If they are destined for Europe, they will be delivered to east coast intermodal facilities where they will be loaded onto ships again. Return (west-bound) trains carry empty containers or containers carrying west-bound products. Railroads try to minimize empties, but the flow of goods is more west-to-east than east-to-west. Sometimes intermodal trains will also have automobile carriers, since these loads have similar mass and similar destinations, and help fill west-bound trains.

As an example of long-distance line-haul operations, an east-bound train might leave the container facility in Los Angeles at three or four in the morning, and go straight to Chicago, stopping only a few times for crew changes, fuel, and the required 1000-mile FRA (Federal Railroad Administration) brake check. The locomotives would likely be assigned to the return trip, after servicing, or some might be assigned to other long-haul duties on the railroad's system, or even rented to work on a competitor's railroad. Some twenty or thirty percent of the rail traffic resembles this long-haul pattern. Other traffic may be slower and heavier, or make many stops in order to set out or pick up loads.

Normally, traffic crossing the State's eastern border is travelling from one major urban center, such as Chicago, to another urban center, such as Los Angeles. In California, trains probably pass through one of the railroad's service facilities, like Santa Fe's Barstow shop and hump yard (a hump yard is railcar and train classification junction that relies on gravity to move cars). Normally, the train just gets a new crew and fuel. Sometimes the train needs to exchange a defective or service-due locomotive for a fresh one. To exchange an entire consist, which is often easier than pulling out one locomotive, takes 20 - 30 minutes, including crew change. Then, the train may continue on to Chicago or Los Angeles. Line-haul locomotives that enter the state may go directly to a single terminal and immediately turn around or they may make several stops, including service stops, and may even make local train movements, before being assigned to east-bound trains.

Local trains - Local trains are used to set out empty cars and collect loaded ones from shippers along the rail lines, and to deliver loaded cars and collect empty ones from the recipients at the other end. Locals may also include dedicated trains that go short distances (50 - 100 miles) between terminals and shippers or between terminals, stopping little or not at all. Since local trains are shorter than line-haul trains, and usually do not involve steep grades or high speed, they tend to be powered by older and lower-horse-power locomotives that have been retired from line-haul service. However, line-haul locomotives also make local movements, either because local moves help shift locomotives to a different location, or because there is a shortage of dedicated local locomotives and the line-haul locomotives happened to be available. Some railroads find it more efficient to use their line-haul locomotives as locals part-time and have fewer total local locomotives.

Switching - Eventually, the cars collected by local trains arrive at a place, called a terminal or "switch-yard", where they are assembled into line-haul trains. Terminals are characterized by a large number of short tracks, connected by switches, the devices that allow trains to shift from one track to another. *Switching* involves a great deal of starting, stopping, turning, and slow movement, so it is best performed by short, light, low horsepower locomotives designed for the purpose. Railroads often use these special switch locomotives, and they also use old line-haul locomotives for the same purpose. Terminals are often located inside of or next to major shipping ports, like the Port of Oakland or the Port of Long Beach. Other terminals are located at major rail junctions, like Southern Pacific's Roseville Yard or Santa Fe's Barstow yard. With regard to locomotives, "switching" and "yard" are often used interchangeably; they both mean the same in relation to operations or locomotives. In this report we have tried to use "switching" or "switcher" exclusively.

Light-engine trains - Another type of move is called *light engine*, or LE. These are locomotives with no cars. These are occasionally necessary to get power to where it's needed quickly. Locomotives also pull empty cars, like the local deliveries mentioned above, or like regularly scheduled empty container car movements. Obviously, railroad companies prefer to run trains that carry goods and make money, whenever possible.

Passenger trains - Passenger trains, by our definition, come in two varieties: *intercity* (or *interurban*), and *commuter*. Amtrak is the predominant owner and operator of intercity trains. Some of these trains (such as the *Capitols*) operate wholly within California; others travel across the country. Commuter trains (such as those of L.A.'s MetroLink) are administered by local government agencies in the Bay Area and the LA - San Diego area. Amtrak has been hired to operate some of those services.

2.2 California Rail Lines

There are three major railroads operating in California. The Interstate Commerce Commission (ICC), the agency of the federal government that carries out the provisions of the Interstate Commerce Act and other laws regulating interstate transportation, refers to railroads in terms of their annual revenue - a Class I railroad has $96 million or more annual revenue; a Class II has $19 to $96 million; a Class III has up to $19 million. However, we prefer a distinction that tells more what a railroad does, rather than how big it is. Large railroads (like the big three that operate in California) tend to be *point-to-point* railroads, that is, they move cargo between large terminals. Other railroads are *feeders*, which move cargo short distances, between shippers and the point-to-point railroads (as with local trains, discussed in Section 2.1).

One (imperfect) measure of railroad transportation services is the number of gross ton miles (GTM). This is equal to the distance travelled by every train, multiplied by the total mass of the train, including lading, cars, and locomotives. Two related measures are trailing ton miles (TTM), which counts the mass of cars and lading, but not locomotives, and net ton miles (NTM), which counts the mass of the lading only. The Southern Pacific Transportation Company (SP), hauled 38 billion gross ton-miles of freight in California in 1991 (Harstad, 1992). In 1992 Union Pacific Railroad (UP) averaged 27 billion annual gross ton-miles (based on the first five months), which is about 7% of their 390 billion system-wide total (Reimers, 1992). The Atchison, Topeka, and Santa Fe Railroad (Santa Fe, or SF), hauled about 23 billion gross ton-miles in California in 1991, which was about 15% of the 157 billion gross ton-mile system-wide total (Stehly, 1993). Many tons of freight (quantity figures unavailable) were hauled by the state's 25 or so shortline, regional, and terminal railroads, while millions of passengers moved on the state's commuter systems and Amtrak.

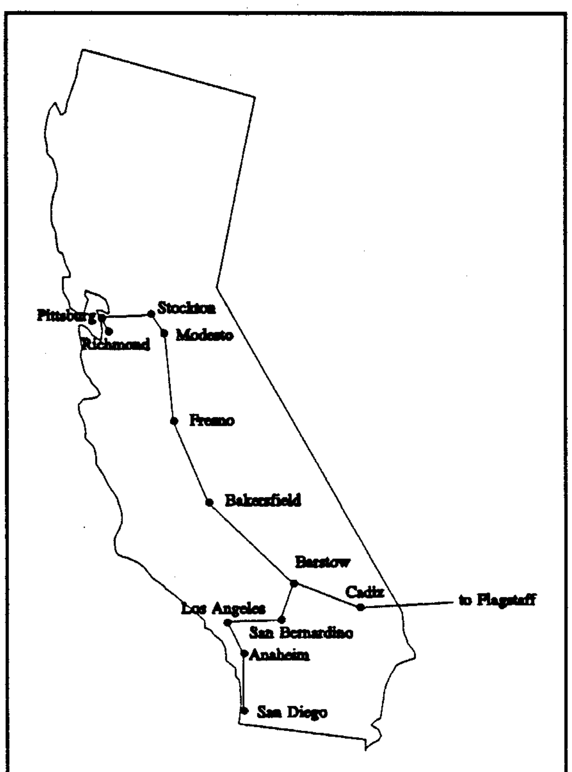

Figure 5: Atchison, Topeka, and Santa Fe Railway Company mainlines in California.

There are 5,800 miles of Class I-owned track in California (*Railroad Facts*, 1992), plus some track now owned by regional transit authorities, and there are five major and eight minor California rail border crossings. There is a <u>northern</u> crossing, owned by Southern Pacific, that crosses into California from Oregon directly north of the Lake Shasta region, enters the Central Valley at Redding and on into the Sacramento area. There is a central crossing; one line, also SP, climbs the Sierra mountains between Reno and Sacramento, and traverses numerous grades, tunnels, and sharp curves on the way; north of Reno, the Union Pacific crosses the Sierras via the Feather River Valley on its way to Salt Lake City (the former Western Pacific route). In the southern part of the state, the Union Pacific crosses west of Las Vegas (another route to Salt Lake City), the Santa Fe has mainline going through Needles, and SP has a mainline connecting Yuma, Arizona and West Colton. Amtrak uses all of these mainlines for their daily trains.

All of the freight railroads run line-haul trains directly from the ports of Los Angeles, Long Beach, and Oakland to major rail termini at Chicago, Houston, and other large mid-western cities. The major ports also serve as terminals for the "land bridge", a scheme where ship-borne foreign origination and foreign destination containers are shipped by rail across the United States rather than through the Panama Canal or around Cape Horn.

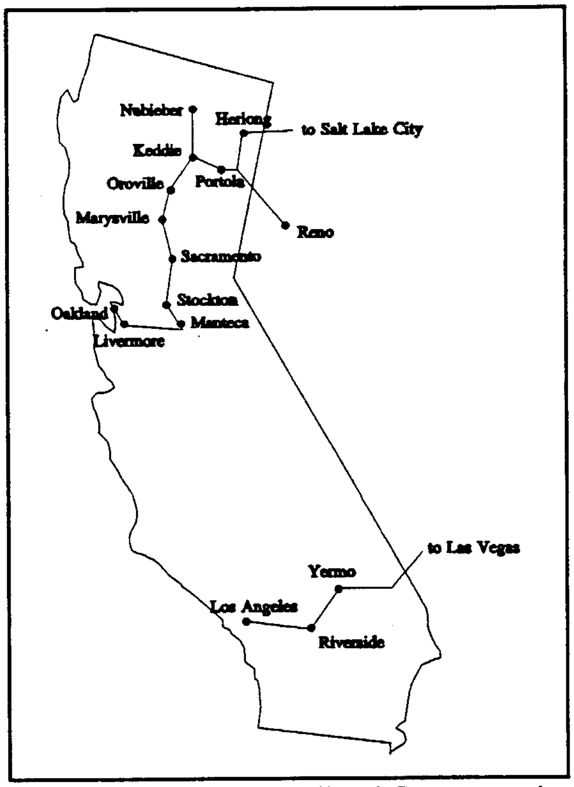

Figure 6: Union Pacific Railroad Company mainlines in California.

Santa Fe - The Santa Fe mainline tracks in California are shown in Figure 5. Since 1899 Santa Fe has leased the rights to use the Southern Pacific line that crosses the Tehachapi Mountains between Barstow and Bakersfield. The Santa Fe tracks in the San Joaquin Valley run essentially parallel to SP's, and they have their own tracks into Oakland, from which they run some 20 trains every day, many of them double-stack container trains.

Santa Fe's major California service facility is at Barstow. Here they change crews, fuel, wash, and sand locomotives, perform minor engine overhauls, true and replace wheels, repair minor body damage, and repair freight cars. In Barstow they also have a large classification yard, which services the entire Los Angeles - San Diego region. Santa Fe intermodal terminals are found at Stockton, Modesto, Fresno, Bakersfield, Barstow, San Bernardino, San Diego, Richmond, and Los Angeles. All Santa Fe trains that enter or leave California go through Barstow. Santa Fe has estimated that an average 64 trains per day (both directions) enter or pass through their Barstow facility.

As further discussed in Section 4, EF&EE assessed the potential for creating a "California only" locomotive fleet, which would interchange power with the "rest of the U.S." fleet at gateway points outside the major urban air basins. As Figure 5 shows, the logical gateway point for the Santa Fe would be its present Barstow facility. These gateway locations are only suggestions, used for cost calculations. The railroads will, of course, choose whatever gateways that best meet their economic and operational needs.

Union Pacific - Figure 6 shows the mainlines of the Union Pacific Railroad (UP) in California. In the last decade UP has gained a much greater share of the California rail market, with the purchase of the Western Pacific Railroad. This connects UP's Salt Lake City mainline with Northern California, crossing the Sierra Nevada near Portola, and reaching Oakland via Stockton and Manteca. In the south, another UP mainline from Salt Lake City passes through Las Vegas and the California desert, and crosses the San Bernardino Mountains not far from Southern Pacific's mainline, continuing on to UP terminals in Los Angeles. Logical UP gateway points would be at Portola on the Northern branch, because it is a California city with a small rail yard and it is outside of the air basins, and at Yermo on the Southern Branch, because it is outside of the air basins and because UP's biggest California shop is there. (Two other shops are at Los Angeles and Stockton.) However, UP personnel have stated that the railroad might choose to put the gateway at Salt Lake, instead, rather than have two isolated systems in California. Since this could involve substantial extra costs, especially for an electrification scenario, a more reasonable approach might be to build gateways at Portola and Yermo, and negotiate trackage rights on either the SF or the SP to allow units to be exchanged between Northern and Southern California.

Southern Pacific - As shown in Figure 7, SP has the greatest mileage of California tracks of all the railroads, and the tracks cross all of the most severe grades in California. In the north, they descend from Oregon through the Cascade mountain range and into the Central Valley town of Redding. The mainline continues to Roseville, just north of Sacramento (there is also a second line to Sacramento, without enough traffic to be considered a mainline). From the central part of the state, SP tracks go through Sparks and Reno, Nevada, climbing the steep, curvy grades of the Sierra Nevada via Donner Pass, and descending again into the flatland at Roseville. The same line continues on to Sacramento and San Jose. A line from San Jose to San Francisco is a mainline by virtue of the 50 commuter trains that run on it every day. In Sacramento a line bends south and connects to all of the agricultural centers of the San Joaquin Valley, and to Bakersfield. A single line connects Bakersfield to West Colton and Los Angeles via the Tehachapi and San Bernardino mountain ranges. Closer to the ocean, a long and lightly used SP line connects San Jose to Los Angeles. To the west, a single mountain, Beaumont Hill, interrupts the desert line that connects the southern part of the SP system to West Colton and Los Angeles, via Yuma, Arizona.

SP's major shops are currently at Sparks (Nevada), Roseville, and Los Angeles, but the LA shop is expected to be sold off as soon as a new West Colton shop is completed.[3] As shown on the map, logical gateways to California for the SP would be at Redding in the North, at Sparks for the Donner Pass line, and at Indio for trains on the Southern route.

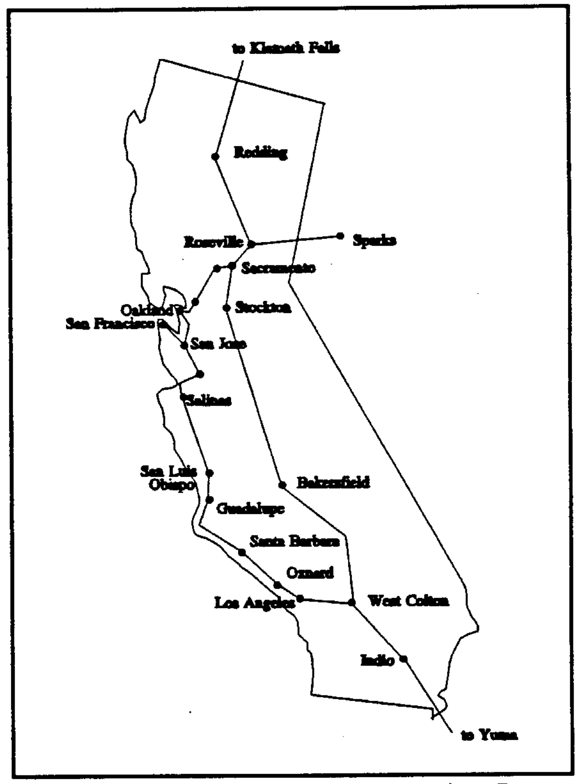

Figure 7: Southern Pacific Transportation Company mainlines in California.

Amtrak - Amtrak does not own any right-of-way in California. Instead, it rents trackage rights from the freight railroads. Out-of-state trains on Amtrak include two per day on the SP central route, two per day on the SP northern route (to Oakland and continuing to Los Angeles on the SP coast route), two per day on the UP southern route, and two every other day on the SP southern route. In-state Amtrak trains include three per day between San Jose and Sacramento, four per day between Oakland and Bakersfield, and ten per day between San Diego and Santa Barbara, via Los Angeles. Amtrak does not operate any trains over the mountains between Bakersfield and Los Angeles - passengers are transported by bus instead.

Generally, Amtrak's service shops are in cities where its long distance trains begin or terminate. Within California, Amtrak services locomotives and cars at Los Angeles, San Diego, and Oakland. Of these, the Los Angeles shop is the largest.

California Shortlines - California has more than 20 shortline railroads, the names and locations of which are indicated in Figure 8. Shortlines range in size from a few employees and a few hundred thousand dollars in annual revenue to 100 employees and many millions of dollars in revenue. The business of the short lines is essentially to move loads from shippers to the large railroads and back, much like the large railroads do with their switch and local operations. Most are quite small; several also run tourist excursion trains on their tracks. Some are terminal railroads, which operate only inside of port facilities. The longest has 167 miles of track, and the shortest has 1.9 miles. All connect to one or more Class I mainlines or branchlines; several are actually owned by or affiliated with one or more Class I railroads. The Modesto and Empire Traction Company boasts two mainline connections, a small intermodal terminal, and 10 well-maintained locomotives. Few of the non-affiliated shortlines run with late-model equipment - 6 of the 82 locomotives in service are obsolete Alcos or Baldwins. Obsolete or not, these locomotives are often purchased for little more than scrap value and kept going with used parts and shoestring maintenance budgets. Shortlines rarely have enough capital to buy new motive power, nor do they (usually) use enough fuel to justify the better fuel economy of new locomotives. However, several shortlines are owned and operated by larger companies, such as Kyle Railways and RailTex.

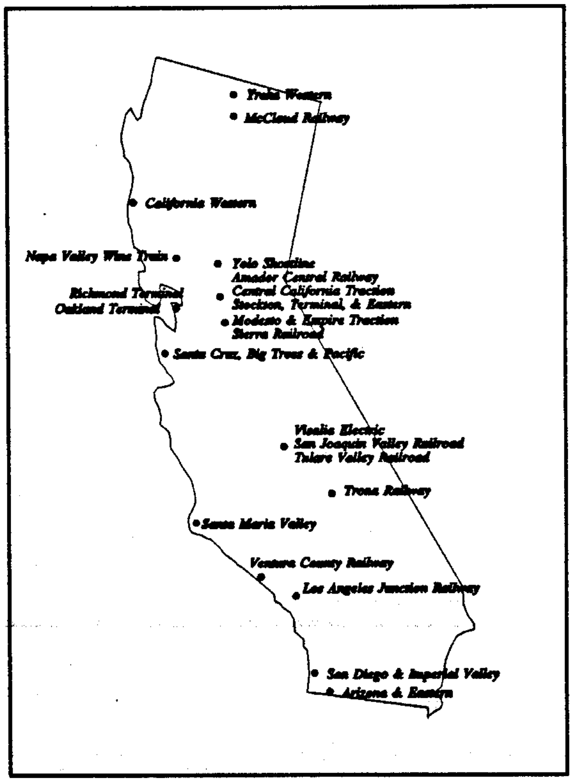

Figure 8: California Shortlines.

<u>Commuter Railroads and Transit Authorities</u> - Passenger trains referred to in this report are heavy commuter trains pulled by diesel locomotives, as opposed to light, self-powered trains like BART (Bay Area Rapid Transit). Although not new to California, commuter trains appear to be undergoing a resurgence. In the Bay Area, the Peninsula Commute Service is now at 50 trains per day between San Francisco and San Jose. Extensions and frequency increases are planned. In the LA region, Orange County runs daily commuter trains, and the Southern California Regional Rail Authority (SCRRA) is operating nine trains per day from downtown Los Angeles to various suburban cities. In terms of gallons per week or month, some intercity and commuter locomotives use as much fuel as line-haul freight locomotives. Since they also operate exclusively in populated areas, they are very significant to air quality concerns.

2.3 <u>Train Dispatching and Scheduling</u>

Since trains cannot turn off the track, and require many miles to slow down from full speed, great care is essential to ensure that they do not run into each other. The original technology for moving trains safely on a single track was the "timetable". Trains were given identifications and sent out with pre-determined precise times of arrival and departure at stations and sidings. No one was allowed to violate the schedule - when a train did not show at its scheduled time and place all other traffic was stopped until the lost train was found. The next improvement to this system was the telegraph, which allowed train orders to be broadcast to remote stations, and for stations to return important information, allowing for running changes in the schedule. Then a signal system was developed that allowed engineers to learn in advance the intrusion of another train on their track space. Manual signals were (are) activated by human operators who were (are) in communication with other operators. Automatic signals, introduced in 1872, divided tracks into insulated sections, called blocks. The tracks are part of a low-voltage DC circuit, with track-side batteries providing the current and the wheels of the trains providing the switch. Any part of the train in a block completes a circuit which indirectly energizes a red (stop) signal by the side of the track, to indicate the presence of the train in that block. Fail-safes built in to the system cause red signals in the event of signal circuit problems and prevent accidental clear signals. Further signal refinements over the years allowed operators to "see" two or more blocks ahead and gave them rough speed limits. Phones between stations replaced the telegraph, and then radio allowed direct communication between trains and dispatchers. Eventually operating departments connected signal indications to centralized operations centers, where dispatchers monitor position of every train in the entire system simultaneously on electronic mural-boards and TV monitors. Union Pacific uses a single system operations center, while Santa Fe operates with a large center in Chicago and several regional centers around the country. Computers help the dispatchers make efficient choices, and they also help operations center personnel call crews and assign motive power. Nearly all of the railroads, large and small, communicate with train operators via radio-telephone, and some even transmit work orders (manifests) to trains with electronic data links.

Assigning which locomotives go on which trains is largely the job of people in a railroad company who specialize in that activity. They use powerful management tools such as linear and integer programs to match available locomotive power to power requirements across the entire railroad, current and future. These programs include predictions of future traffic levels and specific train requirements, as well as the operational and other characteristics of each projected train. They then assign the right locomotive horsepower and locomotive types to each train in order to minimize cost, while ensuring that sufficient power is available in the right place at the right time, and that locomotives receive their scheduled maintenance. Even with this central planning, however, it may still be necessary to juggle locomotive assignments in the field, particularly if an unexpected maintenance problem leads to a breakdown out on the road or makes it necessary to pull a locomotive off of a train.

Equipment breakdowns are extremely expensive, because in the short term they delay service, and in the long term they turn away customers. Railroads have extensive routine preventative maintenance and overhaul programs to avoid breakdowns, but breakdowns inevitably do occur. Routine maintenance and small scale repairs, like turbocharger replacement, exhaust system replacement, and cooling system repairs, are done at smaller service shops. Large scale repairs and overhauls are performed at large, centralized shops, one or two to a railroad. Sometimes locomotives must be hauled shut down, or "dead," to a repair shop. Southern Pacific has estimated the cost of hauling a dead locomotive at $0.0295 per ton-mile, or about $4 to $10 per mile hauled (Harstad, 1992).

2.4 Locomotive and Rolling Stock Technology

Railroads achieve great economies of scale by coupling many cars together, thereby spreading the costs of motive power and crew over many loads. The train is slowed by friction shoe brakes energized by an air system connected to and powered by the locomotives. The average freight train length in the western US is 65 cars long, and average net weight (or weight of lading) is 2,800 tons (*Railroad Facts*, 1992). Trains are normally dispatched with locomotives totalling 1 to 4 horsepower per "trailing" ton (weight of cars and lading only), depending on the speed of service required and terrain anticipated (*Industry Comments, p 66)*. This is less than that of on-road trucks, which typically have 7 to 15 horsepower per gross ton.

Locomotives in the United States are almost exclusively diesel-electrics, powered by 12, 16, or even 20 cylinder diesel "prime movers". The only significant use of electric locomotives in North America is in Amtrak's Northeast Corridor and in Mexico. Electric locomotives are discussed in Chapter 11. In diesel-electric locomotives, the prime mover drives a large alternator, from which the power is rectified, conditioned, and routed to the final drive system, a set of electric motors, one for each axle. This configuration allows the machine to apply maximum torque to the rails at zero forward speed, which is essential for initial train motion. Present locomotive diesel engines range from less than 1200 to 4400 horsepower, with the smaller engines normally found in older locomotives, and the higher horsepower ratings being typical of locomotives produced recently. Within the limits set by wheel-rail adhesion, increasing the horsepower per unit reduces the number of units required to pull a train. Since fewer units cost less to run, railroads have a strong incentive to buy the most powerful locomotives available. Both of the main U.S. locomotive manufacturers have raised their maximum power output from the 3000 HP typical a generation ago to around 4,400 HP, and orders are now being taken for 5000 and 6000 HP locomotives[4].

Passenger locomotives are similar to freight locomotives, except that they must provide 60-cycle AC electric power for car heat, light, and cooling. This is called Head End Power, or HEP. HEP is supplied by a variety of means. Some older locomotives run the prime mover always at synchronous speed, and pull the HEP from the traction alternator power. A more efficient approach is to invert the rectified DC from the traction alternator to 60-cycle AC power. In both of these cases, the same engine supplies both the HEP and the traction power. Another approach is a separate, dedicated engine/alternator for HEP, as with the new EMD F59PH locomotives.

Locomotives do not have throttles in the conventional form - instead power is selected in eight discrete positions called "notches", each corresponding to a pre-determined engine load and speed. The power control also provides an idle position (and "low idle" on recent locomotives), and several gradations of dynamic braking if the locomotive is so equipped. (Dynamic brake is a feature that slows the train by using the electric motor as a generator to dissipate the train's kinetic energy. Kinetic energy is converted to electricity in the traction motors, and then into heat in a large power dissipation grid built into the locomotive. This feature is especially useful in hilly terrain, and nearly all line-haul locomotives on the three California railroads have dynamic braking capability.) The notch feature makes locomotives simpler to operate and more reliable, and coincidentally makes controlling their emissions easier.

Just as with automobile and truck drivers, the skill of the locomotive operator makes a great difference in fuel consumption, efficiency, and emissions. For example, the operator may use power braking, the simultaneous application of throttle and brakes, to obtain good speed control, but at a 40 to 50% penalty in fuel use compared to normal throttle modulation (AAR, 1981). Railroads spend a great deal of effort training their operators and dispatchers to use the most efficient practices.

On older locomotives, auxiliary equipment such as radiator cooling fans, air compressors, and dynamic brake fans were mechanically driven from PTO (Power Take-Off) shafts. On newer, more efficient locomotives, demand-actuated electric motors with electronic controls have replaced PTO fan drives, and electronically-actuated clutches control operation of the air compressor shaft. This means that auxiliaries operate only when they need to, and at the most efficient speeds, resulting in moderate fuel economy gains. Other fuel saving features include blower duct and fan optimization, turbocharger size optimization, injector sizing and tuning, anti wheel-slip devices, and microprocessor control of traction power systems.

The discussion of engine technology is enhanced by an understanding of an important engine characteristic, *mean effective pressure*, or MEP. It is a measure of an engine's ability to do work, independent of engine size, and it is calculated by dividing the work per cycle by the cylinder volume displaced per cycle. It is also an expression of average in-cylinder pressure.

MEP can be expressed easily in terms of engine horsepower:

$$MEP(lb/inch^2) = \frac{Power(hp)\ x\ n_R\ x\ 396{,}000}{V_d\ (inch^3)\ x\ N(rev/\mathrm{min})}$$

where n_R is the number of crank revolutions per power stroke, V_d is the total volume, and N is the engine speed in revolutions per minute. If brake horsepower (or brake torque) is used to calculate the MEP, then the result is called *brake mean effective pressure*, or BMEP.

For a given engine displacement and rotational speed, BMEP is directly related to power output. BMEP is thus a measure of an engine's power output relative to its size. Higher BMEP means greater stress on the engine structure and reciprocating components. Locomotive engine makers have squeezed more power and greater efficiency from their products over the years by steadily increasing the BMEP, with turbocharging and other means. The trend toward higher BMEP in locomotives can be seen in Table 7 by comparing the older EMD 16-645E3 and the newer EMD 16-710G3 engines.

Table 7: Comparison of BMEP for heavy-duty diesel locomotive and truck engines.

Engine	Application	RPM	Power (hp)	BMEP (psi)
Two-stroke Engines				
EMD 16-645E3	Railroad, Marine	896	3,186	136
DDC 6V-92TA	Highway Truck	1200	233[a]	139
DDC 8V-149TI	Mining, Marine	1900	800	140
EMD 16-710G3	Railroad, Marine	903	4,035	156
Four-stroke engines				
CAT G3516-TA	Gas Gen Set (SI)	1200	1,085	170
Cummins KTTA38-C	Mining	1500	1,109	255
DDC Series 60	Highway Truck	1200	331[a]	282
CAT 3612	Gen Set	1000	4,980	292
CAT 3176	Highway Truck	1200	286	300
GE 12-7FDL	Railroad	1050	3,200	301

[a] At peak torque conditions.

Because of the need for maximum power output from an engine which must still fit in the physical confines of the locomotive, diesel engines used in locomotives have high BMEP ratings. It has been claimed by some in the rail industry that very high BMEP levels make locomotive engines fundamentally different from other types of diesel engines, so that emission control techniques applicable to (for example) truck diesels could not be applied to locomotives. As Table 7 shows, however, many highly-rated truck diesel engines have BMEP levels, at maximum torque, that are similar to or even higher than those of locomotive engines.

Locomotive engines are different from truck engines in some other ways, mostly because of their operating environment: they are subject to very high vibration levels, they must operate in tunnels, where not every locomotive in a consist enjoys the benefits of large frontal area cooling (as truck engines do), and they must be reliable enough to operate almost continuously at full load for three months without major service.

2.5 Dimensional Constraints of Trains

Trains cannot climb steep grades, so train tracks often pass through hill tunnels and underneath other structures, such as bridges. The existence of such structures, and the expense of modifying them, has always dictated the exterior dimensions of rail cars and locomotives. Right-of-way and structure costs dominate track and vehicle costs, so the dimensions of tunnels, bridges, and overpasses (codified in "clearance diagrams") determine how tall and wide the trains can be, or conversely, where the movement of taller and wider trains will be restricted. Horizontal restrictions mostly affect special wide-load traffic, while vertical restrictions affect the ever-increasing double-stack container traffic and Amtrak's double-deck "Superliner" equipment. Most western mainlines are tall enough to accommodate double-stacked container trains (which need 20.25 feet of vertical clearance and 8.25 feet of horizontal clearance) and Superliners, but locomotives have traditionally been constrained to AAR clearance diagram "C" (15.5 feet tall by 10.7 feet wide), which allows them to be used on virtually every line in every state. This is a concern especially in the East, where there are many old tunnels and low bridges. In the West, there are no mainline vertical restrictions that affect locomotives. Other limitations are more important; for example, six-axle locomotives cannot enter some lightly-travelled spur lines because of low weight capacity and tight track curvature.

2.6 The Locomotive Environment

The locomotive operating environment is one of the most demanding faced by any type of machinery. Locomotives are designed for continuous duty at full rated power. They must deliver this power using the least amount of fuel possible. They must be able to operate unwaveringly at all altitudes found on US mainline track, while conforming to the envelopes of the tightest tunnels and bridges. They must perform equally well in sub-zero temperatures in the northern Great Plains, in the heat of the desert Southwest, and in snow and rain. In the California mountain passes, they sometimes must operate in all of these extremes at once. In a tunnel, the temperature near the roof often exceeds 100 °F, even in winter, as a train passes through. Only the lead locomotive has the benefit of fresh, cooler air forced through its radiators. The rest of the consist must get by with the heated second-hand air. When the locomotives exit the tunnel they experience a temperature plunge, challenging the fortitude of every locomotive component.

Tractive effort is one measure of locomotive performance, and it is closely related to the locomotive's weight and number of axles. It is the maximum tractive force a locomotive can apply at its coupler (the "hitch"; the device that connects the cars and locomotives together). This force is equal to the product of the weight of the locomotive and the coefficient of friction between the wheels and the rails. Exceeding the maximum tractive effort causes lost adhesion and wheel-spin. Tractive effort is not really a limiting factor unless speeds are less than 25 mph, as when starting, or on steep mountain grades. To increase tractive effort, one can either increase the coefficient of friction (for example, by using sand on the rails), or increase the weight of the locomotive. There is a limit to how much weight can be added, however, as excessive axle loading reduces the fatigue life of wheels and rail. Four-axle locomotives weigh about 280,000 lb., and cannot tolerate much more weight without exceeding the allowable axle loads. For this reason, railroads operating in hilly territory often purchase six axle locomotives to increase tractive effort on long, steep grades. Although equipped with the same engine and alternator as four-axle units, these locomotives have one extra axle and traction motor per truck, and are generally ballasted to maintain the same level of axle loading. A 6-axle locomotive typically weighs about 390,000 pounds, giving about a 50% increase in tractive effort compared to a similar four-axle locomotive. Although better at low-speed "drag" applications, 6-axle locomotives are more costly to operate, as the extra weight must be carried along in flat territory and the additional components must be repaired and maintained (Armstrong, 1990). Therefore, most of the country's six-axle units are in the west where steep mountain grades and low speeds are common.

<u>Energy consumed by trains</u> - In order to move a train, the locomotives must overcome four major forces: rolling resistance, air resistance, start-up inertia, and grades (gravity). The power required to move a train on level track is relatively small: a 3,000 horsepower locomotive can pull more than 5,000 tons at 30 mph (by the Davis Formula, which includes air resistance - Armstrong, 1990). The profile and condition of rails and wheels are minor contributors to friction forces. Rubbing friction between the wheel flanges and the inner side of the rail is a major contributor to rolling resistance. By applying a thin layer of grease to the inner side of the rail, it has been found that this friction and the associated wear can be reduced significantly. The benefits are greatest on curves, but significant friction reductions have been measured even on tangent (straight) track.

Air resistance is less of an energy drain on railroads than it is with some other transport modes. A train's frontal area is small compared to the volume of cargo it carries. Nonetheless, lowering air resistance gives measurable efficiency gains. Aerodynamic car designs have been investigated, and train operators are encouraged to keep boxcar doors closed, which reduces resistance (AAR, 1981). Air resistance will become increasingly important as other efficiency gains are realized, and is very important to high speed passenger trains.

Climbing grades is the most significant consumer of train energy (and precursor to emissions). Climbing a 1 percent grade at 15 MPH takes more than 8 times as much tractive force as pulling on a level track (Armstrong, 1990). The energy invested in getting a train to the top of a hill is mostly lost on the descent, as it is necessary to use the brakes to avoid reaching dangerous speeds. A greater horsepower-per-ton ratio allows a train to get over a hill faster, but results in a fuel penalty on flat ground, as the extra horsepower are not needed, and the engine operates less efficiently at light load. The major grades faced by the main California railroads were discussed in Section 2.2, and include the Sierra Nevada, the Tehachapis, and the San Bernardino mountains. The efficiency of a carrier that moves goods within the state depends on the severity and number of grades it must cross on its routes.

<u>Maintenance</u> - Railroads maintain (or pay to maintain) their own track, rolling stock, physical plant and locomotives. Locomotives owned by a given railroad are normally repaired and serviced by that railroad. Leased locomotives are normally the responsibili-

ty of their lessors, who will oversee major repairs but will likely let the leasing railroad company perform routine maintenance. Routine maintenance includes replacing filters, lubrication, safety inspection, cleaning, downloading from the on-board computer, replacing traction motor brushes, checking cooling water, load testing, and checking locomotive systems for defects. FRA regulations require every locomotive to undergo periodic inspections and service. The typical 90-day service takes 17 hours to complete, including refueling, replenishing the sand, extensive inspections, and waiting for assignment. Despite this extensive (and expensive) program of preventive maintenance and inspection, unscheduled service problems are not uncommon. The manager of one railroad shop in California estimated that two-thirds of the locomotives entering that shop did so for unscheduled maintenance, compared to one third for scheduled maintenance and inspections. Since inspections are scheduled every 90 days, this implies that unscheduled maintenance must have been required about once every 45 days, on average. Since such repairs frequently take several days, this has an important impact on locomotive utilization. Other railroads appear to have a somewhat better record on unscheduled maintenance, but such problems are common on all. Such problems might be more frequent on older locomotives, as components which are not normally replaced or rebuilt wear out or fatigue.

3. BASELINE DATA AND TECHNICAL APPROACH

EF&EE's evaluation of locomotive emission control measures proceeded through the following six steps:

1. Screening analysis. Potential locomotive emission control measures were screened and subjected to preliminary analysis to identify the most promising measures for detailed analysis. The report of this screening analysis was published in January, 1992 (Weaver, McGregor, and Turner, 1992). Section 3.1 of this chapter summarizes the screening approach and results.

2. Baseline characterization. Baseline fuel consumption and emission data were developed for four typical locomotive models chosen to represent a range of manufacturers and technologies. The results of this characterization are given in Section 3.2 of this chapter.

3. Assessment of California fleet requirements. Since it would be most practical and cost-effective to apply many of the measures considered to a separate "California only" locomotive fleet, EF&EE estimated the number of locomotives required in such a fleet, as well as the incremental capital and operating costs (additional costs above planned expenditures) of setting up "gateways" to exchange California and non-California power. The results of this analysis are presented in Chapter 4.

4. Detailed evaluation and costing. The most promising of the measures considered in the screening report were re-examined using the additional extensive data collected by EF&EE through more than a year of research, including extensive contacts with railroad representatives and a number of site visits. The results of this evaluation are given in Chapters 5 through 11; some of the common elements of the analysis are discussed in Section 3.3 of this Chapter. Three options (LNG, SCR, and electrification) were examined in detail. Capital and operating costs and emission impacts were estimated on a per-locomotive basis for each technology (except electrification) in each of the four locomotive types considered. For electrification, the capital and operating costs and emission benefit of electrifying the major California mainlines were estimated, using the results of published

studies. The next steps required to implement each technology, and the time required to do so were also characterized for each case.

5. Cost-effectiveness analysis and technology selection. EF&EE combined the results of the preceding tasks to estimate the total emission reduction, costs, and cost-effectiveness of each technology. These evaluations were carried out separately for line-haul and local/switching operations. Based on this analysis, EF&EE was able to define the tradeoffs between emission control and costs, and recommend a final cost-effective level of emission control. This analysis is documented in Chapter 12.

6. Regulatory analysis. EF&EE developed a proposed regulatory structure. After review and comment by the railroads, EF&EE finalized these recommendations, including an estimate of costs of monitoring and enforcement, which were then factored back into the cost-effectiveness estimates. Details of the proposed regulatory structure and costs are given in Chapter 13.

3.1 Technology Screening

EF&EE's screening analysis concluded that a wide variety of measures and techniques have the potential to reduce locomotive emissions, either by reducing the amount of fuel required to move a given volume of traffic, by reducing the emissions per unit of fuel burned, or by substituting a "cleaner" source of motive power for the present diesel engine. The specific results of the screening analysis are summarized below.

Diesel engine modifications - Within the near term (2-4 years) it should be possible to develop and implement "engineered" retrofit packages incorporating retarded injection timing, improved injectors, enhanced charge air cooling, and possibly other modifications for existing locomotive engines. These could be expected to reduce NOx emission by around 40-50% from current levels, and would be highly cost-effective compared to other alternatives considered. In the longer term, locomotive manufacturers will have to develop engines meeting EPA emission standards. If this technology is available for retrofit to existing engines, it could be highly cost-effective. US locomotive repair capacity exists to retrofit 100 to 150 locomotives per year, meaning that enough locomotives to cover most of California's needs could be converted in 4 to 5 years.

Replacement or rebuilding of diesel locomotives with low-emitting designs - Existing high-speed engine designs related to heavy-duty truck engine technology constitute a viable alternative to large-bore engines in switchers and local-service locomotives. Because of their similarity to truck diesels, it should be possible to incorporate recent advances in truck engine emission control technology in these engines at moderate cost. Although locomotives undergo a substantially different duty cycle from trucks, emission control technology developed for truck engines would be applicable and equally effective in similar engines used in locomotives. In fact, engine designers would find it *easier* to control emissions under locomotive operating conditions (primarily steady-state operation at one of a few defined conditions) than under the transient and highly variable operating conditions experienced by trucks. Substitution of remanufactured locomotives incorporating such emission-controlled engines for existing switch and local-service units could be cost-effective on emission grounds, and would also entail significant operating benefits. In the case of line-haul locomotives, outright replacement of existing units with new ones meeting expected federal emission standards could be justified on cost-effectiveness grounds, once such new locomotives become available.

Diesel fuel modifications - Potential diesel fuel modifications include reducing sulfur to 0.05% by weight, and reducing aromatic content. Low sulfur content is now required in motor vehicle diesel fuel in California, and at least some of the railroads are purchasing this fuel for locomotive use in the state, due to its better availability. Low-aromatic fuel (or its equivalent in emission performance) was required for diesel motor vehicles in California in 1993. The cost-effectiveness of low-aromatic fuel for NOx control is poor compared to other NOx control techniques, however, and the emission reductions achievable through this approach are relatively small.

Diesel aftertreatment devices - Trap-oxidizers for particulate control are unlikely to be useful with locomotives, as the available data suggest that the particulate is nearly all lubricating oil and unburned fuel, which are not collected efficiently by the trap. Catalytic converters are likely to be a better choice. Selective catalytic reduction (SCR) for control of NOx appears quite feasible for locomotive applications, and could be quite cost-effective at around $1,500 per ton of NOx. A number of SCR catalyst technologies are available; one - the precious-metal catalyst - could also serve as a catalytic converter for particulate and HC emissions.

Measures to reduce diesel fuel consumption - Measures to reduce diesel fuel consumption (and thus emissions) by locomotives in California include reduced idling, improved train handling and dispatching, and rail lubrication. Total potential savings by these measures are of the order of 10-20% of fuel consumption, but it is not clear what fraction of this potential may already have been realized. To achieve and sustain the maximum potential reduction in fuel consumption will require significant improvements in monitoring and control by railroad management and by the ARB. These improvements in monitoring and control, as well as similar improvements in operating costs and efficiency, could be provided through a new technology known as Advanced Train Control Systems (ATCS). ATCS technology would provide railroad management the tools needed to optimize locomotive utilization and maintenance, as well as most other aspects of railroad operations, and is capable of providing a real-time record of the operating condition and location of each locomotive operating in California. These data could be combined with locomotive emission measurements to give, in effect, continuous emission monitoring for every locomotive, and could thus serve as the basis for enforcing either command-and-control type regulations or the proposed "bubble" concept.

Alternative fuels - Feasible alternative fuels for locomotives include methanol and liquified natural gas (LNG). Methanol, although technically feasible, would not be cost-effective compared to alternatives such as diesel engine modifications and SCR. LNG, on the other hand, could produce both an 80 to 90% reduction in NOx emission and a substantial savings on fuel costs. LNG locomotive engines could be either dual-fuel (gas/diesel) or spark-ignition designs; recent technological advances in dual-fuel engines offer emission levels competitive with those of spark-ignition engines. LNG would be carried on-board the locomotive and/or in a separate tender. One dual-fuel locomotive/tender combination (although not optimized for emission) is already being tested by the Burlington Northern. From our preliminary assessment, LNG used in low-emission engines appears to be one of the most attractive options available for controlling locomotive emissions. The infrastructure and safety issues of LNG will be discussed further in Chapter 10.

Railway electrification - By transferring the electric generation process from the locomotive to a remote power plant, electrification could dramatically reduce emissions from locomotives in urban areas. However, the capital costs of electrification would limit its use to heavily trafficked lines, so that it could practically be used only for line-haul applications. Emissions from local and switching locomotives would need to be addressed by some other means. Even limited to mainline applications, the capital costs of electrification might exceed the capabilities of the California railroads, which means substantial government involvement could be required. In this analysis, EF&EE was unable to identify any significant savings in operating costs which could offset the high capital costs of this option, although there was some savings in fuel costs and savings in total locomotive units. As revealed in Chapter 11 of this report, the cost-effectiveness of electrification as an emission control measure is about $16,000 per ton of NOx eliminated (plus or minus $5000, depending on whose electrification estimates are used). This is much more than that of the other options identified, but close to SCAQMD and the ARB guidelines of $25,000 per ton and $10-12,000 per ton, respectively. Close scrutiny of electrification is warranted because of the political concerns associated with possible government assistance for electrification, the technical risks involved, and the delays inherent in constructing such a large system, especially when compared to favorable cost-effective options. However, electrification also improves emissions of HC, CO, and particulates, which should be accounted for.

3.2 Baseline Characterization

Calculation Methodology

In order to arrive at total emission reductions one could simply change the locomotive engine emission factor and fleet data by appropriate amounts in the Booz-Allen spreadsheets and recalculate the totals. Given all the differences between our goals and the Booz-Allen report's goals, we elected to determine emission and fuel consumption totals on a per locomotive basis, then multiply by fleet estimates to get state-wide totals. We used Booz-Allen results and comments from the railroads to double-check our results. This was particularly important for the line-haul fleet size estimate, which was crucial to our calculation and for which only indirectly related data were available.

Selection of representative locomotives

Given the diversity of locomotive designs, it was not possible to carry out a detailed evaluation of each technology for each locomotive model. Instead, our strategy was to select four representative locomotive models, and apply emission control technologies to them. These locomotives represent those most commonly used in the state by the three major freight railroads, now and (most likely) in the next ten years. This is not to say that these are the only models that could be converted - for example, we did not include any passenger locomotives and most certainly the conversions could be adapted to them - but simply that these are the most likely candidates and the models for which we have the best data. Once the models were chosen, baseline fuel and emission data were collected and totals were calculated, using the most relevant duty cycles. The base data and the calculations were all entered into linked spreadsheets, so that the effects of changes in duty cycles or base data could readily be observed. The tables of base data and the spreadsheets containing cost-effectiveness calculations were also linked.

The first locomotive model considered is the EMD GP38-2 (EMD uses "GP" to denote four-axle units and "SD" to denote six-axle units). This is a low power (2000 hp) locomotive, first built in 1966. It is commonly used in California in switching and local service. Originally designed as a road locomotive, it has been supplanted by newer, more powerful models, and is now used in these less-demanding applications. Union Pacific has some 350 of these units, Santa Fe has 69, and Southern Pacific has 44 (numbers are system-wide, not California). Other very similar models also in use are the GP35, GP38, and GP39, which we do not address specifically in the analysis, but which are generally similar. The engine is a Roots supercharged (mechanical forced induction) 16 cylinder 2-stroke. The GP40 is also similar, but has a more powerful turbocharged engine, for line-haul service. Many of the units in use in California are equipped with dynamic brakes. The GP38's age and its four-axle configuration mean it is likely to see continued switcher service in this decade.

The second model is the EMD SD40-2. Similar models include the SD40, SDP40-2, and SD40-2L. The SD45 is a similar model but larger, with a 20 cylinder, 3600 HP engine. Although in the process of being supplanted by newer, more powerful units on some roads, SD40-2s and SD45-2s are still the mainstay of most line-haul locomotive fleets in the West. The SD40 model dates back to 1966, while the SD40-2 (similar, but with an upgraded control system) replaced it in 1972. SP has some 320 SD40-2 locomotives in its system, Santa Fe has 220, and UP has around 960. They are road or local locomotives with turbocharged 16 cylinder, 2-stroke, 3000 HP engines. Less than a quarter of these locomotives are tunnel versions (SD40-2T), manufactured specifically for Southern Pacific, in which the engine intake air is routed from down low, to avoid higher temperatures found at the tunnel ceiling. The tunnel models are longer and have more free space available than the non-tunnel models. We will concentrate on the non-tunnel versions, but the emission control technologies considered can be applied equally well to the tunnel locomotives.

Although 3000 HP locomotives are not purchased new anymore, they will populate the aging fleet for some time and so should be included in the planning of retrofit packages. As rebuilt units, they will continue to perform line-haul-type work, and as retired line-hauls with high tractive effort they will no doubt perform extended service hauling local trains. Southern Pacific plans to rebuild a large number of SD40-2 and SD45-2 locomotives over the next 5 years (Harstad, March, 1992), and Union Pacific plans to rebuild its entire SD40-2 fleet before 2003 (Reimers, February, 1992). (Note that recent developments in locomotive technology have raised questions about the continuing viability of 3000 HP locomotives in line-haul service. See the *Industry Comments* and Appendix C of this report).

The EMD F40PH passenger locomotive is similar to the GP40 in that it uses the same engine and the same axle configuration, but with different gearing for greater speed[5]. It is different in that its carbody covers the entire locomotive, not just the engine, and that the engine's alternator is used for power for the trailing units, for heat, air conditioning, and light (HEP). That means the engine revolves at synchronous speed (900 rpm) at all times, increasing its NOx and noise emissions. There are almost 100 F40PHs in use in California. We have chosen not to address this as a separate, distinctive model, since most of the issues of conversion are the same as for the SD40-2.

The next candidate is the EMD GP60. The GP60 is a modern 3900 hp, four-axle road locomotive. This model was chosen because it represents the latest engine technology EMD has to offer, the 710G series, and is of the power and configuration most likely to be purchased new and leased by the railroads in the near future, for use on the high-volume intermodal routes in and out of California. The 710 engine replaces the 645E series used on the GP50 and SD50. The engine is a turbocharged, 16 cylinder two-stroke. Southern Pacific has about 170 of these on its roster, Santa Fe has 125, and Union Pacific has none (although it does have 300 SD60's, a similar but larger and heavier six-axle unit). The GP70 and SD70 models, although newer, use the same powerplant. The GP60's duties in the next decade will be mostly high volume line-haul operation, with little local service.

The fourth choice is a General Electric Dash 8 - 40B (similar models are the B39-8 and B40-8W). The Dash 8 - 40B is the latest in road locomotive technology from GE, a 4000 hp, four-axle line-haul unit. The six-axle version is designated 40C. The 40B is used in both passenger and freight service. Although GEs are not nearly as common as EMDs nationwide, in the West the Dash 8s have shown exemplary performance on steep terrain and in high-speed line-haul service, owing to high efficiency, high power (fewer total units are needed), and advanced traction control. The Dash 8 40B and 40C are equipped with the 7FDL-16 4000 HP turbocharged engine. Southern Pacific owns or runs 90 of these, Santa Fe has 100, and Union Pacific has 380. Union Pacific perhaps prefers this model over the EMD 60-series locomotives.

This report uses these locomotives to demonstrate the feasibility of proposed emission reduction technologies, and sets the baseline for further research and development. A discussion of costs, technology availability, engineering risks, development lead time, and emission reduction potential, relevant to each model and several locomotive duty cycles, is included in each section.

Baseline Fuel and Emission Data

The incremental costs and emission reductions associated with each emission control measure were estimated by comparing the total costs and emissions to the present (1987) diesel baseline (with some modifications, discussed below). Thus, in order to establish the baseline for comparison, it was necessary to estimate average annual emission and fuel consumption for the existing fleet of diesel locomotives. This section documents the baseline estimates developed.

Duty cycle and annual fuel use - Estimated duty cycles (the percentage of time spent in each operating mode) were contained in the Booz-Allen inventory study (Booz-Allen, 1991). Table 8 through Table 10 contain the duty cycle numbers from the Booz report, modified in one important way. The line-haul duty cycles calculated by Booz-Allen were not adjusted for the time when locomotives are unavailable for work, such as time spent in the shop. The actual locomotive *availability* is about 88%, or 321 days out of the year. Note that availability is not a function of the schedule or frequency of trains; the locomotive roster is adjusted to fit the availability performance. The locomotive *utilization*, the time that a locomotive is actually pulling trains rather than waiting for assignment, is estimated at 65%[6]. In this analysis, the difference was added to the "off" time in the Booz-Allen duty cycles, to more realistically represent locomotive performance and annual fuel consumption. The engines sometimes idle while in the shop or waiting for assignment, but based on our observations at several California shops we believe this mode does not contribute substantially to emissions.

Estimated fuel consumption, based on the Booz-Allen duty cycles, was reported in our screening report. Comments from the rail industry indicate that the duty cycles were reasonable, but total fuel consumption per locomotive was too high. This is probably because there was little or no "off" time in the original duty cycles. This has been corrected by the adjustments described above.

Table 8: Baseline duty cycle, fuel consumption, and NOx emission for EMD GP38-2 in yard/switch service.

Throttle Notch	Avg. Fuel Cons. (gal/hr)	Percent time in notch	Weighted fuel cons. (gals/hr)	Percent fuel cons. in notch	Weighted NOx (lb/hr)
off	0	31.6%	0.00	0.0%	0.00
brake	13	0.0%	0.00	0.0%	0.00
idle	5	55.4%	2.53	36.6%	1.52
1	7	3.2%	0.24	3.4%	0.13
2	17	3.2%	0.55	8.0%	0.31
3	30	2.2%	0.67	9.7%	0.40
4	46	2.2%	1.04	15.0%	0.61
5	63	0.8%	0.48	7.0%	0.28
6	81	0.4%	0.31	4.5%	0.20
7	103	0.0%	0.00	0.0%	0.00
8	124	0.9%	1.09	15.7%	0.67
Avg. fuel consumption, gals/hour					6.9
Fuel consumed, gals/year					53,337
NOx emissions, tons/yr					15.9

The data on locomotive fuel consumption in each operating notch for the GP38, SD40-2, and B40-8 came from the results of extensive testing performed by Scott Labs, and reported by the Association of American Railroads (AAR) Research and Test Department (Conlon, 1988). Fuel consumption for the EMD GP60, a model which post-dates the Conlon report, was taken from CalTrans/SwRI data (Fritz, 1992). Emission data came from the same sources, except for the GP38-2 model, which data came from the Booz-Allen report.

Table 8 shows the estimated duty cycle and fuel consumption for an EMD GP38-2, in switch service, defined by the average of the two duty cycles reported in the Booz-Allen study, with modifications as discussed previously[7]. As the table shows, switcher units experience very light duty, with more than 55% of their time and 36% of their fuel consumed in idling. Switchers are normally assigned to a specific geographic location, so that all of the resulting emissions would be produced in the same area. Based on the calculations used to produce Table 8, the GP38 locomotive uses about 53,000 gallons of fuel per year (within the 6-basin region).

Table 9 shows the estimated duty cycle for the SD40-2 locomotive in local service, based on the data given in the Booz-Allen report. The resulting average fuel consumption data (based on similar assumptions to those discussed for switchers) are also shown. As this table shows, 47% of the cycle is spent at idle, which also accounts for 21% of fuel consumption. Notch 8 (full power) operation, on the other hand, accounts for only 2.1%

of the time, but 27% of fuel consumption. Based on the Booz-Allen data and our estimates of availability, average annual fuel consumption per locomotive in local service is about 104,000 gallons per year.

Table 9: Estimated duty cycle, fuel consumption and NOx emission for EMD SD40-2 locomotive in local service.

Throttle Notch	Avg. Fuel Cons. (gal/hr)	Percent time in notch	Weighted fuel cons. (gals/hr)	Percent fuel consump in notch	Weighted NOx (lb/hr)
off	0	35.8%	0.00	0.0%	0.00
brake	19	1.2%	0.22	1.6%	0.10
idle	6	47.1%	2.82	20.9%	1.45
1	12	2.9%	0.34	2.5%	0.21
2	22	2.7%	0.59	4.4%	0.29
3	40	2.6%	1.03	7.6%	0.47
4	56	2.2%	1.25	9.2%	0.53
5	78	1.4%	1.09	8.1%	0.48
6	102	1.1%	1.09	8.1%	0.46
7	146	1.0%	1.40	10.4%	0.61
8	172	2.1%	3.67	27.2%	1.63
Avg. fuel consumption, gals/hour					13.5
Fuel consumed, gals/year					104,135
NOx emissions, tons/yr					24.0

While a number of sub-categories of line-haul locomotives and line-haul service types can be defined (e.g. intermodal freight, mixed freight, unit train, and passenger), all of these types of service have more in common with each other than with local or switching duty, and we have chosen to combine them in the present analysis. Table 10 shows the estimated average duty cycle for line-haul locomotives in California, and the resulting fuel consumption of the EMD GP60, GE B40-8, and EMD SD40-2 locomotives, based on the data in the Booz-Allen report and on data from manufacturers. Since we expect the EMD SD40-2 to serve in both line-haul *and* local applications for some years to come, we have calculated its fuel use in both duty cycles. As the table shows, 40% of line-haul locomotive operating time is still spent at idle, however, this mode accounts for only 5 to 7% of fuel consumption. Fully 51% of the fuel used is burned in notch 8 (full power), while notches 5 through 7 account for another 27% of fuel consumption. Average fuel consumption per locomotive is estimated at 287,000, 294,000, and 260,000 gallons per year for the GP60, the B40-8, and the SD40-2, respectively. Note that the SD40 consumes almost as much fuel as the GP60, even though it has 800 less horsepower; this is a testament to the improved efficiency of the 710G-series engine.

Alone of the three major California railroads, Santa Fe actually measures the fuel consumed in its locomotives. In their comments on the Technology Screening Report, Santa Fe representatives indicated that their average line-haul fuel consumption was quite a bit less than suggested by the Booz-Allen duty cycles. The low value cited by the Santa Fe was 205,000 gallons, the high value was 390,000 gallons, and the average was 301,000 gallons. These estimates are based on current fleet rosters and duty cycles, and so include more high horsepower locomotives, smaller consists, and higher efficiency operations than those of 1987. Nonetheless, we believe that a downward adjustment of

Table 10: Estimated duty cycle and fuel consumption for EMD GP60, GE B40-8, and SD40-2 locomotives in line-haul service.

		EMD GP60			GE B40-8			EMD SD40-2		
Throttle Notch	Percent time in notch	Avg. Fuel Cons. (gal/hr)	Weighted fuel cons. (gals/hr)	Percent fuel consump in notch	Avg. Fuel Cons. (gal/hr)	Weighted fuel cons. (gals/hr)	Percent fuel consump in notch	Avg. Fuel Cons. (gal/hr)	Weighted fuel cons. (gals/hr)	Percent fuel consump in notch
off	23.0%	0.0	0.0	0.0%	0.0	0.0	0.0%	0.0	0.0	0.0%
brake	6.1%	15.1	0.9	2.4%	12.6	0.8	2.0%	18.9	1.1	3.4%
idle	39.7%	6.2	2.4	6.3%	4.6	1.8	4.7%	6.0	2.4	7.1%
1	3.0%	17.4	0.5	1.3%	12.6	0.4	1.0%	11.9	0.4	1.0%
2	3.2%	27.0	0.9	2.2%	22.4	0.7	1.9%	22.0	0.7	2.1%
3	3.1%	48.5	1.5	3.9%	51.3	1.6	4.1%	40.1	1.2	3.7%
4	3.9%	70.1	2.7	7.0%	73.1	2.8	7.4%	55.6	2.2	6.4%
5	3.1%	91.4	2.9	7.4%	104.0	3.3	8.6%	78.3	2.5	7.3%
6	2.9%	108.9	3.1	8.1%	135.3	3.9	10.2%	102.0	2.9	8.7%
7	2.2%	158.6	3.5	9.1%	163.9	3.6	9.5%	145.7	3.2	9.6%
8	9.9%	202.5	20.1	52.1%	194.3	19.3	50.6%	171.7	17.1	50.7%
Avg. fuel consumption, gals/hour				38.6			38.2			33.7
Fuel consumed, gals/year				297,490			294,296			'40

the Booz-Allen calculations was justified. This adjustment is reflected in the calculations discussed above, and followed the methodology discussed in the second paragraph of this section. Santa Fe's switcher estimate was 40,000 gallons per year and their local estimate was 100,000 to 110,000 gallons per year. EF&EE calculations indicate that, all other parameters being the same, a switcher would have to be used less than 200 days per year in order to use only 40,000 gallons of fuel. This may certainly be the case for many of the shortline railroads[8], some of which operate seasonally or part-time, but switchers based in large urban yards could use more than 40,000 gallons per year.

Although passenger train emissions were not a significant portion of the Booz-Allen 1987 inventory, the recent trend towards expanded commuter and intercity service (to wit, the Amtrak *Capitol* now at three trains—and planned to go to ten trains—7 days per week; the Amtrak *San Joaquin*, initially at one and now at four trains per day; and the Los Angeles Metrolink service, which now traverses three South Coast counties daily) suggest that passenger train emissions may *become* significant, especially in dense urban areas. Also, there is considerable evidence that diesel-powered rail service actually emits more NOx than the individual car trips it replaces (SCRRA, 1992).

Table 11 shows a representative duty cycle from Amtrak's *Capitol* passenger service between San Jose and Sacramento, taken from Amtrak data (Burk, 1992b). The profile shown is the actual time in each notch for one day's operation of one locomotive, and so reflects the style of operation of the engineers on duty, but should be close to that of typical intercity and commuter trains that operate wholly within California. It will not reflect the increased idle time during the winter months. This particular train, like most of the California passenger services, operates on level ground, stops every 5 to 10 miles, dwells 1 to 3 minutes at every stop, and runs only during the daytime. There is little dynamic brake operation, no operation in notches 1 or 2, and almost 10 hours of every day are "off" hours. This profile does not likely resemble those of other Amtrak trains, which cross mountains, stop less often, and run 24 hours a day.

Table 11: Duty cycle and fuel use for EMD F40PH locomotive in Amtrak *Capitol* service.

Throttle Notch	Avg. Fuel Cons. (gal/hr)	Percent time in notch	Weighted fuel cons. (gals/hr)	Percent fuel cons. in notch	Weighted NOx (lb/hr)
off	0	41.4%	0.00	0.0%	0.00
brake	21	0.4%	0.09	0.3%	0.04
idle	6	29.7%	1.63	5.5%	5.69
1	16	0.0%	0.00	0.0%	0.00
2	16	0.0%	0.00	0.0%	0.00
3	41	6.2%	2.56	8.7%	1.41
4	57	6.0%	3.46	11.7%	1.86
5	79	4.0%	3.18	10.8%	1.70
6	109	2.9%	3.16	10.7%	1.59
7	146	1.1%	1.62	5.5%	1.01
8	168	8.3%	13.86	46.9%	8.97
Avg. fuel consumption, gals/hour					29.6
Fuel consumed, gals/year					227,857
NOx emissions, tons/yr					85.8

Engines in the F40PH locomotives used by Amtrak (and also CalTrain) must run at full rotational speed, even at "idle", in order to supply stable-frequency power to the passenger cars. The passenger locomotive fuel consumption in this duty cycle is similar to that of a line-haul freight locomotive, at 228,000 gallons per year, assuming an 88% availability (321 days). Notch 8 accounts for 47% of the fuel consumed, and notches 4, 5, and 6 account for 31%. The annual NOx emission is 86 tons, actually higher than any of the freight locomotives. Most importantly, most of the California passenger train emissions occur inside the state, and most of that in air basins. Not all of the California locomotives produce this much NOx, but too many more that do would contribute significantly to the emission inventory.

The same duty cycles used to calculate fuel use in Table 10 were used in Table 12 to calculate NOx emissions, based on the best available data for the three locomotive types. The SD40-2 model has three-quarters of the annual emissions of the other two models; this is partially because it has three-quarters of the horsepower.

<u>Emission factors and annual emissions</u> - Booz-Allen also estimated emission factors for locomotives used by each of the three main railroads in California in each class of

service. These factors were based on each railroad's locomotive roster, together with manufacturer and SwRI (Southwest Research Institute) data on emissions in each notch for each engine type. The resulting values probably underestimate locomotive HC and PM emissions, since they are based only on relatively new locomotives in good mechanical condition. The NOx emission factors, on the other hand, are probably fairly accurate, as NOx emissions from diesel engines generally do not change much with time.

Table 12: NOx emission of line-haul locomotives.

		EMD GP60		GE B40-8		EMD SD40-2	
Throttle Notch	**Percent time in notch**	**Baseline NOx (lb/hr)**	**Weighted NOx (lb/hr)**	**Baseline NOx (lb/hr)**	**Weighted NOx (lb/hr)**	**Baseline NOx (lb/hr)**	**Weighted NOx (lb/hr)**
off	23.0%	0.0	0.0	0.0	0.0	0.0	0.0
brake	6.1%	6.8	0.4	3.2	0.2	8.4	0.5
idle	39.7%	3.4	1.3	0.7	0.3	3.1	1.2
1	3.0%	10.2	0.3	6.7	0.2	7.4	0.2
2	3.2%	18.1	0.6	13.2	0.4	10.7	0.3
3	3.1%	32.8	1.0	27.6	0.8	18.3	0.6
4	3.9%	37.4	1.4	46.1	1.8	23.7	0.9
5	3.1%	43.6	1.4	82.8	2.6	34.5	1.1
6	2.9%	51.6	1.5	76.7	2.2	43.0	1.2
7	2.2%	74.7	1.7	93.7	2.1	63.7	1.4
8	9.9%	112.3	11.2	105.6	10.5	76.2	7.6
Total NOx (lb/hr)			20.8		21.1		15.1
Total NOx (tons/yr)			**80.0**		**81.3**		**58.1**

For this final report, EF&EE calculated annual NOx emissions for each of the locomotives that were selected for detailed study. This allowed direct comparison between models for conversion cost and cost-effectiveness. The estimate of switcher NOx emissions by notch shown in the right-hand column of Table 8 shows that more than a third of the emissions occur at idle. Another 36% of the emissions are spread over the low-power notch positions 1 through 4, and the remaining 27% occur in the higher-power modes. For local service, on the other hand, the high-power modes account for 54% of NOx emissions, versus 20% for idle (Table 9); and in line-haul locomotives, the high-power modes account for more than 75% of total emissions (Table 12). We also calculated annual HC, CO, and PM emissions for all of the locomotive models. These values, plus the annual fuel consumption and NOx emissions, are shown in Table 13..

3.3 Detailed Evaluation and Costing

The detailed assessments of the various emission control technologies considered are discussed in Chapters 5 through 11. For all of the technologies except electrification, the evaluation was based on an assessment of the technology in each of the four locomotive models described above. Where necessary, preliminary designs were prepared to confirm that the technology could feasibly be packaged in the locomotive. Details of the assessment of each technology are provided in the applicable chapters. Certain aspects of the cost-effectiveness evaluation are common to all of the assessments, however, and are discussed here.

Table 13: Summary of emissions for locomotive models.

	Fuel cons. (gals/yr)	NOx (tons/yr)	HC (tons/yr)	CO (tons/yr)	PM (tons/yr)
EMD GP60 line-haul	297,490	80.0	2.3	5.8	1.5
GE B40-8 line-haul	294,296	81.3	2.9	8.4	1.5
EMD SD40-2 line-haul	259,440	58.1	3.0	10.0	1.4
EMD SD40-2 local	104,135	24.0	1.8	4.5	0.6
EMD GP38-2 yard	53,337	15.9	0.8	2.1	0.3
EMD F40PH Amtrak	227,857	85.8	2.3	6.9	1.2

For this study, EF&EE calculated the cost-effectiveness of the different emissions control measures by dividing the increase in "annualized" life-cycle cost due to each measure by the estimated reduction in annual NOx emissions. Thus, if a measure were projected to increase the life-cycle cost by $1,000, and would reduce NOx emissions by two tons, the cost-effectiveness would be $1,000/2 or $500 per ton. Although it is recognized that many of the measures considered would also affect emissions of HC, CO, SOx, and/or particulate emissions, the primary focus is on reducing emissions of NOx. In addition, there is presently no generally agreed and accepted way to incorporate effects on different pollutants (HC, NOx, PM, etc.) in a single cost-effectiveness calculation. Although measures such as a "damage index" have been used in some analyses, these measures remain highly controversial. Since the results of the cost-effectiveness analysis show that many emission control measures would be highly cost-effective even when evaluated for their NOx benefits alone, it was not considered necessary to complicate the issue by introducing more sophisticated measures of emissions benefits.

The numerator in the cost-effectiveness calculation is the estimated increase in the annualized life-cycle cost to society due to the adoption of the measure. This includes the increase in annual operating costs, as well as the "annualized" value of the initial capital costs of implementing the measure. The "annualized" capital cost is equivalent to the loan payment required to pay off the initial capital investment over its useful life. For this analysis, EF&EE used a real (inflation adjusted) discount rate of 8% per year, compounded annually. A higher value, 17%, was claimed by the railroads[9]. The EF&EE estimate was based on the annual "cost of capital" estimate for railroads, published each year by the ICC. For 1991, the ICC value was 11.6% (*Railway Age*, 1991b). This value is not adjusted to account for the effects of inflation. Allowing for annual inflation of 3.6% resulted in a real discount rate of 8%. Since interest rates (and therefore the costs of capital) have declined markedly in the last few years, we consider this a reasonable estimate. Much of the money required to implement emission controls would likely be borrowed (at real interest rates currently less than 5% after adjusting for inflation), so that if anything this estimate may be somewhat on the high side.

4. DEDICATED "CALIFORNIA-ONLY" FLEET

As discussed in Chapter 2, line-haul locomotives are not restricted to a particular geographic area—instead, they operate anywhere on the railroad that they may be needed, and even on other railroads under "run through" agreements. A train from Los Angeles to Chicago will normally retain the same set of locomotives the whole trip. Upon arrival in Chicago, the same locomotives may be sent back to Los Angeles pulling another train, but they may equally well be dispatched to Houston, or even "run through" on another line to New York. Switch locomotives, on the other hand, are generally assigned to a specific area at any one time, but may also be re-assigned depending on traffic, maintenance needs, etc. A locomotive used for local service may remain in the same area for considerable periods, but there is also significant locomotive interchange between local and line-haul operations. Locomotive assignment and dispatching to ensure that adequate power is available where and when it is needed is a complex scheduling and optimization problem. On major railroads, it is carried out by experts often assisted by sophisticated computer software.

If California adopts locomotive emission regulations, we expect that the affected railroads would probably move first to reduce emissions from their switching and local-service fleets in California by acquiring low-emission locomotives or modifying the existing locomotives to reduce their emissions. We expect them to attack switching and local emissions first because: one, low-emission equipment is already available in those sizes; two, it is less risky to operate them in revenue service; and three, locals and switchers operate full time in air basins[10]. This change would not pose major operational problems, as there is little need to interchange switchers and local units between California and other states. For line-haul locomotives, the situation would be considerably more difficult. One option would be for the railroads to use low-emission locomotives for the entire journey on every train going to or from California. This would require a large number of emission-controlled locomotives, which could not move around the country like ordinary locomotives. The second option would be to use low-emitting locomotives only within the air-pollution control area, interchanging with ordinary (higher-emitting) locomotives at "gateway" points.

Which of these options is chosen will depend primarily on cost. The first option would require that most of each railroad's line-haul locomotive fleet be low-emitting, while the second option would require a much smaller number of low-emitting units, but added costs and lost time due to the interchange process. If the cost of reducing locomotive emission is low (or if other states follow California in adopting emission requirements), railroads will likely choose to control emissions from their entire fleet, rather than suffer the additional costs and complexity of changing power. On the other hand, changing power at a gateway would be the only practical way to implement railway electrification or other expensive measures.

In this chapter we evaluate how many line-haul, local, and switching locomotives would be required to make up a dedicated California locomotive fleet, as well as the capital and operational costs involved in changing locomotive power at gateway points.

4.1 Assumptions

In current practice, railroads use line-haul locomotives from a nationwide power pool. The assignment of locomotives to trains is done in such a way as to minimize capital and operating costs, while still meeting schedule requirements. For the three Class I freight railroads operating in California, some 5 - 15% of their locomotive population is in California at any given time, but the fleet changes constantly as locomotives enter and depart. In a dedicated California-only fleet scheme, the railroads would stop trains at points that we call gateways, which would be located outside of the air basins. The incoming locomotive consist would be removed, and a separate consist of low-emission locomotives would be substituted, whereupon the train would continue to its destination. The same low-emission locomotives would bring out-bound trains to meet conventional (49-state) locomotives at the gateway, where the interchange would proceed in reverse. Of course, if the gateway location included a classification yard (as might be the case for Santa Fe, in Barstow), many trains would simply originate or terminate at the gateway itself.

One advantage to requiring low-emission locomotives exclusively, from a regulator's point of view, is that enforcement is as easy as identifying the correct equipment (understanding, of course, that periodic assurance of that equipment's emission performance is still necessary). A major disadvantage of this approach, from the railroads' point of view, is that it would reduce their flexibility in assigning power. This would require more locomotives overall, due to the need to maintain separate reserves of California and non-California locomotives. This disadvantage would be minimized under the more flexible "bubble" approach proposed in this study. Under the bubble, non-California locomotives could enter the air basins if necessary (e.g., in case of an unexpected breakdown, or unusual market demands), as long as their emissions were accounted for and included in the railroad's basin-wide total.

In estimating the costs and other impacts of switching power between California and non-California locomotives, we took into account the following:

- The power demand for the three freight railroads often peaks at different times[11], so that additional power can be traded (rented) from and to competitors (as is done now) to handle traffic surges. (Amtrak has less flexibility in this regard, since it must use at least one passenger locomotive per train, for HEP);

- Even under a California-only fleet scheme, railroads will probably be allowed to bring 49-state equipment in when necessary for emergencies, as long as a system is in place to account for those locomotives and their emissions;

- It is beneficial to change power at places where railroads normally stop for other reasons, such as locomotive service. In assessing potential gateway locations, EF&EE took into account the location and capabilities of each railroad's existing shops;

- Reducing emissions outside the air basins is of little value[12], and EF&EE assumed that it would not be required. This implies that gateways need not be located at the state border, but can be located at the nearest appropriate points outside the air basins;

- Three facts suggest that it would be advantageous for railroads to assign their older, high-traction, six-axle locomotives such as the SD40-2 to California service, while keeping the newest and highest-powered units for the longer hauls, in 49-state service: one, the utilization (as discussed in Section 3.2) of a fleet of California locomotives dedicated to relatively short trips, would be poor compared to the 49-state fleet, and it makes economic sense to assign the newest machinery to the highest utilization routes; two, the steepest grades on railway lines (sometimes called "ruling grades") leaving California are inside California, between the center of the state and our proposed gateways, making high traction a desirable attribute; three, there are some 1100 high-horsepower locomotives parked (good operating condition, but not in service) nationwide (*Railway Age*, 1992c), and many of these are high-traction, six-axle locomotives[13]. We predict that these parked locomotives will be rebuilt for revenue low-emission service and therefore, new ones to replace them will not be needed.

4.2 Locomotive Populations

Our calculations of locomotive populations and required reserves for a dedicated California fleet are based on the idea that the number of line-haul locomotives a railroad requires in California will be roughly in proportion to the ratio of that railroad's California Gross Ton-Miles (GTM) to its system-wide GTM[14]. These data are shown in Table 14 for the three major lines. Southern Pacific has the highest percentage of GTM in California at 22.6%, Santa Fe is second at 14.7%, and Union Pacific is third at 7.0%. The number of trains per day crossing the border is also roughly proportional to California and nationwide Gross Ton-Miles.

Table 14: US and California Gross Ton-Miles.

	California Gross Ton-Miles	Systemwide Total Gross Ton-Miles	CA percent of total
Southern Pacific	19,570	86,575	22.6%
Union Pacific[a]	27,166	389,395	7.0%
Santa Fe	23,120	157,390	14.7%

[a] From 1992 monthly average (Reimers, 1992b).

Table 15 lists our estimates of the average number of line-haul, local, and switch locomotives operating in California, for each railroad. Locomotive populations are constantly changing, and we estimated which locomotives in the roster were currently assigned to revenue service, so these numbers are only approximate. The derivation of these numbers is discussed below.

Table 15: Estimates of California locomotive population.

	Total US	Total California	Northern California	Central California	Southern California	Sub-total
Southern Pacific						
Line-hauls	1,279	289	51	51	101	202
Locals		160	40	40	80	160
Switchers		142	20	34	88	142
Union Pacific						
Line-hauls	2,241	156	0	79	46	125
Locals		28	0	14	14	28
Switchers		25	0	8	17	25
Santa Fe						
Line-hauls	1,413	202	0	0	162	162
Locals		47	0	0	47	47
Switchers		33	0	0	33	33
Passenger/Amtrak						
Regional	N/A	90	0	30	60	90
Interstate	N/A	7	2	2	3	7
Switchers	N/A	4	0	1	3	4
Shortlines/Regionals						
Line-hauls			0	0	0	0
Locals			0	0	0	0
Switchers			21	38	8	67

The Southern Pacific line-haul population was estimated by multiplying the SP "CA percent of total", from Table 14, by the SP system-wide line-haul locomotive roster, the first column in Table 15 (1,279 X 22.6% = 289). This means that, on average, 289 SP line-haul locomotives can be found in California. Southern Pacific estimates that half of their line-haul units[15] in California, and up to one-quarter of their switchers, are shopped (for service or to await assignment) at any one time. We assume those locomotives awaiting assignment would be included in the "available" population, however, we were not able to obtain data to show what percentage of those shopped were actually on the ready tracks awaiting assignment. Using our observations from on-site visits we estimated that the available line-hauls was less by one-third (30%), meaning that of the 289 units physically in California, only 202 are ready to work[16]. We also needed an estimate of what proportions of those locomotives could be found in the three geographic divisions. Assuming 25% of the 202 line-haul locomotives work the northern or central routes, and 50% work the southern route (EF&EE estimates, based on study of industry journals and other publications; Southern Pacific states the number is close to 78%; see *Industry Comments*, Section 11, page 45), 51 are in the North and Central, and 101 are in the South. Southern Pacific supplied its own estimates of average California locomotive population (Harstad, 1992), including 160 locals and 142 switchers. The geographic division of locals and switchers are again EF&EE estimates, based on discussions with the industry, track miles, and yard locations.

For the Union Pacific line-haul units, the California locomotive population was estimated by multiplying the ratio of UP's California and system-wide GTM (Table 14) by the total number of active line-haul locomotives in UP's roster (Table 15; 2,241 X 7% = 156; numbers may be slightly off due to rounding error). Reasoning that UP also has line-haul units tied up in service shops or performing local train duties, but to a lesser extent than SP since they are smaller in California and do more repair elsewhere, we made the available locomotives 80% of the active locomotives. This means that only 125 of the 156 units, as estimated using GTM ratios, are available to work. Assuming none of the 125 are found in the north, 37% work the central route, and 63% work the southern route (EF&EE estimates, based on anecdotal evidence), 79 are in Central California and 46 are in the Southern California. UP supplied numbers for local locomotive assignments, from which we subtracted the assignments which are totally or mostly outside of the air basins. The net total was 28. The switcher population is UP's most recent count of 25.

Santa Fe supplied an estimate of California and system-wide GTM (Table 14) and a recent locomotive roster (first column, Table 15). The product of these two is our estimate of active line-haul locomotives in California (1,413 X 14.7% = 202). Reasoning that SF is like UP in their ratio of shopped-to-working locomotives, we assumed only 80% of those 202 are actually ready to work. All of these are attributed to Southern California, since SF has only the one route. Santa Fe also supplied a roster of dual-purpose switcher/local locomotives, which we classified according to horsepower (33 switcher and 47 local) (Stehly, 1992c). In actuality, Santa Fe does not distinguish between local and line-haul in California; they mostly use the same locomotives for both duties.

Passenger locomotives in California are owned by Amtrak, Caltrans, the Peninsula Corridor Joint Powers Board (owners of the CalTrain service), and the Southern California Regional Rail Authority (for Metrolink and OCTC). Their populations are outlined in Table 15. Instead of line-haul and local, we use the labels "Regional" and "Interstate"; both of these are counted as line-haul in the final tally. Forty-two Amtrak locomotives are permanently assigned to the Los Angeles - San Diego area (Keller, 1992a), four work the *Capitol* out of Oakland, six are on the *San Joaquin*, and seven locomotives are in intercity service that on a given day are hauling trains between California and Chicago, Seattle, or New Orleans. The CalTrain commuter service has 20 locomotives, and Metrolink has 18. The state line-haul total, not including the 9-locomotive purchase planned by Caltrans, is 97. Amtrak has 3 switchers in Los Angeles and 1 in Oakland. There are no passenger locomotives which we label "local".

The shortline and regional railroads supplied locomotive rosters, and some supplied fuel data. These railroads vary a great deal in size and traffic, but most are small and use old locomotives in duty cycles even lighter than the switcher cycle we described in Section 3.2. Some companies operate seasonally, and some rotate their locomotives through the shops and storage tracks, as a way of increasing availability. We have elected to treat all shortline locomotives as switchers. We have included locomotives of shortlines that are owned by Class I railroads, but they are a small percentage of the total (Lewis, 1986), so there is little double-counting. We have not included locomotives likely to pull only passenger excursion trains. The total is 67, with most of those located in the Central Valley. The actual number eventually subject to emission controls will probably be less, since there will likely be some kind of exemption for very small railroads (discussed in Chapter 13).

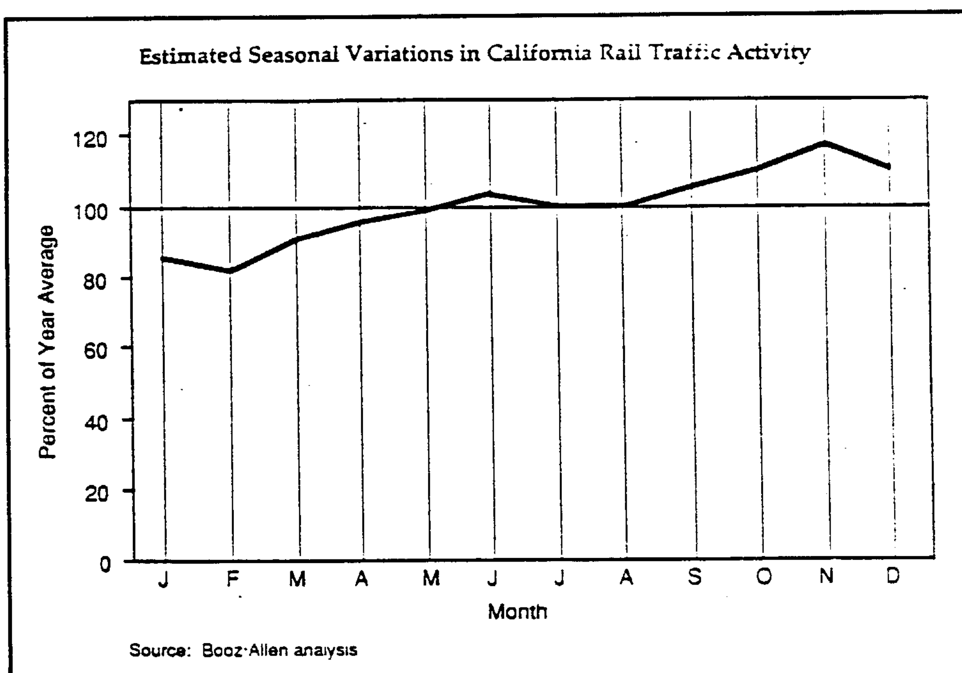

Figure 9: Seasonal variation of California rail traffic.

<u>Reserve Requirement</u> - The estimated line-haul locomotive populations listed in Table 15 are our estimates of the average number believed to be actively working or available for work inside the state's borders. A California locomotive fleet might

need to be larger than the average number of present California units because traffic varies seasonally, and because there is a need for additional reserve power at the gateways.

Figure 9 (from Booz-Allen, 1992) shows how traffic varies over a typical year, with a peak around November and a valley around February. There is a small peak in June, which is probably due to peak harvest season. The November traffic peak, since it does not coincide with any harvests, is probably due to the Christmas retail trade, and so is a national peak, not just a California peak. At present, railroads handle some seasonal increases in traffic with leased equipment, by the week or by the hour. Other cyclic increases are handled by intentionally shifting power to the West (or wherever demand has increased). Capacity to meet an overall national increase in traffic is reflected in the size of the locomotive rosters supplied to us. Since our estimate of California locomotives is just a portion of the total, national traffic capacity is accounted for, and we believe that it is not necessary to add more locomotives to cover seasonal demand.

A dedicated California locomotive fleet will require reserve locomotives because inbound and outbound locomotives cannot be expected to meet their counterparts at the interchange every time and in the needed quantity. Trains move 24 hours per day, and train movements are spaced more or less evenly throughout the day, but sometimes they do collect in bunches. In the ideal case, a locomotive consist could pull a train into the gateway, be "cut off", and then quickly attached to another train going the other direction. In the real world, however, there will always be expected and unexpected variation in demand, variation in train size, and also breakdowns. Therefore, each railroad will need to maintain a reserve of locomotives, both 49-state and California low-emission versions, at their gateways, in order to avoid excessive delays.

An estimate the number of reserve line-haul locomotives needed starts with the average number of locomotives crossing the border gateway, as shown in Table 16 (we are assuming trains are evenly spaced throughout the day).

We estimated that Southern Pacific had a total of 42 trains per day passing in and out of the state. This estimate was based on data from the Booz-Allen inventory study, plus our own observations.[17] We conservatively assume that the greatest period between trains arriving at the gateway would be 4 hours, and so SP would need to keep 4 hours worth of locomotives in reserve at all times (making it convenient to calculate average locomotives per hour for each geographic route). We assume each train uses 4 locomotives (a round estimate agreeing with Booz-Allen and industry data), so we specify a minimum of 4 locomotives at each gateway. The total locomotives appearing per hour at the northern gateway <u>in both directions</u> is 10 trains per day, times 4 locomotives per train, divided by 24 hours per day, which is about 1.7. The central gateway figures are the same. We round these up to 2 per hour, so with a four hour cushion the total is 8. The total locomotives appearing per hour at the southern gateway <u>in both directions</u> is equal to 22 trains per day, times 4 locomotives per train, divided by 24 hours per day, which is about 3.7. We conservatively round this to 4, so that with a four hour cushion the total is 16 at this gateway.

Table 16: Trains and locomotives crossing California borders.

	Northern	Central	Southern	Total
Southern Pacific				
Trains per day	10	10	22	42
Locomotives per hour	1.7	1.7	3.7	7.0
Minimum support	8	8	16	32
Union Pacific				
Trains per day	none	16	24	40
Locomotives per hour	none	2.7	4.0	6.7
Minimum support	none	12	16	28
Santa Fe				
Trains per day	none	none	37	37
Locomotives per hour	none	none	6.2	6.2
Minimum support	none	none	24	24
Amtrak				
Trains per day	2	2	3	7
Locomotives per hour	0.2	0.2	0.3	0.6
Minimum support	2	2	4	8

For Union Pacific, at total of 40 trains per day pass through their two border crossings, 16 at their Central California (ex-Western Pacific) line, and 24 at their Southern California (Yermo) line (Brimley, 1993). We again assume that the greatest period between trains arriving at each gateway would be 4 hours, and so UP would need to keep 4 hours worth of locomotives in reserve at all times. Again, a minimum of 4 locomotives is required for each gateway. The total locomotives appearing per hour at the central gateway <u>in both directions</u> is equal to 16 trains per day, times 4 locomotives per train, divided by 24 hours per day, which is about 2.7. This being a low number we conservatively round it <u>up</u> to 3 per hour, so with a four hour cushion the total is 12. The total locomotives appearing per hour at the southern gateway <u>in both directions</u> is equal to 24 trains per day, times 4 locomotives per train, divided by 24 hours per day, which is exactly 4. With a four hour cushion the total is 16 at this gateway.

For Santa Fe, the number of trains per day through their only border crossing (Needles, Ca) was 37 (McGinn, 1993; Harper, 1993). We again assume that the greatest period between trains arriving at each gateway would be 4 hours, and therefore SF would need to keep 4 hours worth of locomotives in reserve at all times. Again, a minimum of 4 locomotives is required for each gateway. The total Santa Fe locomotives appearing per hour at the gateway <u>in both directions</u> is equal to 37 trains per day, times 4 locomotives per train, divided by 24 hours per day, which is about 6.2. We can afford to be a little liberal and round this off to 6 per hour, so with a four hour cushion the total is 24.

The number of Amtrak trains per day, 7, is taken from the Fall '92 schedule. As with the freight railroads, the number of trains per day was converted to a number of locomotives per hour, but this time assuming that each train has only two locomotives (the standard Amtrak consist). By this assumption Amtrak has 0.2 locomotives per hour at its northern and central gateways and 0.3 locomotives per hour at the southern gateway[18]. We know that more than 4 hours passes between train arrivals (at least in the north and central routes), but we will conservatively assume that the greatest period between trains arriving at each gateway is still 4 hours. Even so, the calculation results in less than 1 locomotive at the northern and central gateways (0.2 X 4 = 0.8), so we must invoke the minimum for those routes, which for Amtrak is two. This poses a dilemma. If we have two locomotives on standby at the gateway, one would be have to be 49-state and the other would have to be low-emission, meaning that it would not be possible to put a proper full consist (two locomotives) on either inbound or outbound trains. We could increase the standbys to four, two for inbound and two for outbound, but then we will have doubled the number of expensive locomotives standing by, idle. Since the Amtrak gateways will be located at the freight gateways (it would be prohibitively expensive for Amtrak to operate its own facilities)[19], and since Amtrak absolutely needs only one passenger locomotive per train and can use a freight unit for the other (in extreme cases), we can justify one reserve for each direction at the northern and central gateways. Remember, these are *reserve* locomotives, to be used in the event scheduled locomotives are broken down or otherwise not available. In the southern route, we have conservatively given Amtrak the full complement of two inbound and two outbound, even though the calculation suggests only one is needed[20].

The final tally of locomotives shown in Table 16 include inbound and outbound locomotives, for a total of 92. Santa Fe would need 24 locomotives, UP would need 28, SP would need 32, and Amtrak would need 8 (the freight tally was not increased to reflect the case of Amtrak needing to use a freight unit; we believe this would be a rare enough occurrence to preclude the need to obtain additional reserve equipment). Half of these would be low-emission versions, and half would be 49-state versions. The total number of locomotives that would need to be converted to low-emission versions is shown in Table 17. All line-haul, local, switcher, passenger, and shortline locomotives are included.

Table 17: Total low-emission locomotives required.

Sub-total line-haul	586
Sub-total Local	235
Sub-total Switcher	271
Sub-total Reserve	46
Total	**1,138**

Our assessment of the number of reserve locomotives required may well be over-conservative. Observation of many rail facilities now shows a significant number of locomotives standing idle, and overall locomotive utilization of the order of 65% leaves substantial room for improvement with improved management and scheduling. Railroads are already developing many of the management and engineering tools needed to handle locomotive interchange efficiently and with minimum reserve requirements. For example, Union Pacific's Locomotive Management System (LMS) is a large, computer-based, real-time linear program that helps UP managers reduce the train-hours-waiting-power (*Progressive Railroading*, 1991a). The system optimizes for daily and seasonal horsepower requirements, fuel efficiency, maintenance cost, and shop availability.

4.3 Capital and Operating Costs

Table 18: Incremental costs of dedicated line-haul fleet.

	Santa Fe	Union Pacific	Southern Pacific	Amtrak /Pass.	Totals
49-state reserves	12	14	16	4	46
Low-emissions reserves	12	14	16	4	46
Service shops		1	1		2
Track upgrade package, 6 @ $2 million ea.					$12,000,000
New 49-state locos at $1.0 million ea.					$46,000,000
Low-emission locos at $800 thousand ea.					$36,800,000
Cost of service shops at $18 million ea.					$36,000,000
Additional one-time-only expenses					$1,800,000
Annualized cost of capital					$13,322,269
Annual O/M cost (not including fuel)					$9,292,000
Annual cost of train delay (including fuel)					$1,705,109
Total Incremental Annual Cost					**$24,409,378**

Capital costs - The capital costs of establishing a California-only locomotive fleet would include the costs of additional locomotives needed to provide the necessary reserve, and the costs of facilities at the gateway locations, as well as the costs of any emission-related changes to the locomotives themselves. We have taken the information shown in Table 15 and Table 16 and estimated the costs of the additional locomotives for all four railroads. The results are shown in Table 18.

Of the 92 additional locomotives estimated to be required to provide adequate reserves, 46 would be low-emission California units, and 46 would be non-California, 49-state units. The non-California units were assumed to be purchased new, at a cost of $1.0 million each. [SP recently paid EMD between $1.2 and $1.4 million each for 50 locomotives (*Railway Age*, 1993a). Prior to that, CN North America bought 40 GE "high horsepower" locomotives for $40 million (*Railway Age*, 1992b). [The railroads argue that freight locomotives cost upwards of $2 million (Industry Comments, Section 11, p. 46), but this seems to refer to high-horsepower, AC traction units.] To supply the California fleet, we expect the railroads would choose to overhaul and upgrade existing *laid up* (parked, not operating) units rather than buy new ones. Each of the three main California lines already has a remanufacturing program for locomotives such as SD40-2s, SD45-2s, and GP40-2s. As discussed in Section 4.1, these units would be better suited to California service than the newer, higher-powered units. We estimate the cost of remanufacturing and upgrading such a unit to current standards at around $800,000 (Peoria Locomotive Works, 1992), excluding the costs of any specialized emission controls (this is a low volume, custom unit price; we would expect the price to be lower if all 46 units were remanufactured at once). The costs of the emission controls would vary with the technology involved; these costs are discussed in the sections on each technology.

In addition to the purchase costs of the extra locomotives, the establishment of the gateway sites would involve some costs for new facilities[21]. It would be most advantageous to locate locomotive service facilities at the gateways, since they could then serve both in-state and out-of-state locomotive populations, and since locomotives would be available immediately following repairs. It was assumed that Southern Pacific would need to build one new service shop at Redding, and would move its planned West Colton shop to Indio. Only the cost of the new shop is included, since SP is paying to build one new shop already, and it is estimated at $18 million, the same SP has budgeted for West Colton[22]. We believe that a one-time-only cost penalty for moving the West Colton shop should be included, since that cost is attributable to cleaning the air in the basin. We estimate that $1.8 million (equal to $90,000 per year for the 20 year economic life) sufficiently covers that move.

For the Union Pacific, a new shop and yard would be required at Portola or in western Nevada, which we have estimated will cost the same as the SP shop. No new facilities would be required for Santa Fe, since the existing Barstow facility is ideally located. ~~The two shops cost a total $36 million.~~

In addition to new shop facilities, each gateway would doubtless require some new track and other modifications to efficiently accommodate the change of power. These costs have been estimated (roughly) at $2 million per gateway, for a total of $12 million, an EF&EE estimate based on generic track cost information taken from rail trade magazines such as *Railway Age* and *Progressive Railroading*.

The locomotive and facilities costs ($12 + $46 + $36.8 + $36 million) are annualized at 8% interest, and for a 20 year term, for an equivalent annual capital cost of $13,300,000. Although we know the buildings will certainly last longer than 20 years, their *economic* life will be little more than 20.

<u>Operating costs</u> - Since we assume gateways are located at crew change points[23] (or that crew change points are moved to coincide with the gateways), there would be no extra labor cost associated with stopping the train. The additional locomotives would incur an annual scheduled maintenance cost of $101,000 per locomotive, the average of SP's $128,000 estimate (Harstad, 1992), and UP's $75,000 estimate (Reimers, Feb, 1992a), for a total of $9,300,000 per year (92 locomotives x $101,000 per locomotive).

The cost of delaying each train for 30 minutes at the gateway should also be included in the operating costs (we believe the railroads would not tolerate delay greater than 30 minutes, which is about the time it now takes to change locomotive consist and crew). First, we determine what portion of a year 30 minutes is:

The next step is to determine the average cost in capital per idle train for that 30 minutes, that is, the cost to the railroad of not being able to use their capital investment for 30

$$\frac{0.5\ hours}{365\ days/year\ X\ 24\ hours/day} = 0.00005708\ year$$

minutes every day. The total trains per day, 126, is given in Table 16. The average cars in a western train is 65.3 (Railroad Facts, 1991). We estimate the capital cost per car at $100,000 (the range is about $30,000 to $150,000, again, our estimate based on trade journal information). The days in a year is 365, the cost of money is 8% per year, and the portion of a year that we are tieing up that money was calculated above. The total cost is just the product of these factors:

126 *trains/yr* *X* .00005708 *yr* *X* 365 *days/yr* *X* 0.08 *%/year*
X 65.3 *cars/train* *X* $100,000/*car*
= $1,371,300/*year*

Next we wish to add the fuel cost of idling all the trains at the gateways. Again, each of the 126 trains per day sits idling for a half-hour. Each locomotive burns 5 gallons of diesel fuel per hour, and there are 4 locomotives per train. Each gallon of diesel fuel costs $0.70. Then the fuel cost of idling is the product of these factors:

126 *trains/day* *X* 365 *days/yr* *X* 0.5 *hr* *X* 5 *gallons/locomotive-hr*
X 4 *locomotives/train* *X* $0.70/*gallon*
= $321,930/*yr*

The total annual operating cost for the whole fleet is just the sum of the cost of idle capital and the fuel cost of idling, about $1.7 million.

The total incremental annual cost (the total costs of converting to a dedicated fleet minus the costs of planned or expected improvements) is the one-time-only cost divided by the 20 year finance period, plus the annualized cost of capital, plus the annual O/M cost, and plus the annual cost of train delay, or about $24.4 million. Thus, a dedicated California-only fleet for freight and passenger operations would cost about $24 million per year for 20 years.

5. MEASURES TO REDUCE FUEL CONSUMPTION

Techniques for reducing fuel consumption by reducing the amount of work required from the engine include rail lubrication, improving train handling, improving train scheduling and locomotive utilization, and reducing idle time by turning off locomotives when not in use. In each case, emissions should be reduced roughly in proportion to the decrease in fuel consumption (more-than-proportionally in the case of reduced idle time, since HC and CO emission factors for idling are several times higher than for operation under load). These measures also have the advantage of being fairly quick to implement, in most cases, and of being very cost-effective (when the cost of implementing and maintaining these measures is less than the cost of fuel saved, they result in net cost reductions). In addition, the social cost of the pollution due to burning a gallon of fuel is several times the cost of the fuel. By determining the fuel consumed per ton of NOx emitted and dividing into the SCAQMD cost-effectiveness guideline of $25,000 per ton of NOx removed we can show the value to society of eliminating NOx emission:

$$\frac{\$25{,}000/\mathit{ton\ NOx}}{294{,}296\ \mathit{gallons\ fuel}\ X\ 1\ \mathit{year}/81.3\ \mathit{tons\ NOx}} = \$6.91$$

The range is $5 to nearly $10, depending on the fuel and NOx values. Thus, fuel conservation measures for emission control may be justified to a much greater extent than they would be from a cost reduction standpoint alone.

5.1 Present Situation

Most railroads have already undertaken extensive fuel-conservation programs, in response to the high fuel prices of the early 1980's. In formal statements made in 1992 some railroads stated there was little additional fuel economy to be gained. However, many conservation measures involve inconvenience to or additional effort from the workers involved, and — in the absence of effective enforcement — tend to fall into disuse. This is not surprising, as these measures have little to do with moving trains on time. Ensuring the effectiveness of such measures will therefore require more than simply adopting a policy - it will be necessary to follow up to ensure that the policy is actually complied with.

Figure 10 illustrates the increase in fuel-efficiency of the Santa Fe (Stehly, 1992a). The units are gallons per 1000 ton-miles, covering the period 1981 to 1991. As the figure shows, the amount of fuel required to move a ton of freight one mile decreased almost every year during that period. Much of this efficiency benefit is due to upgrading locomotives to newer, more efficient models, as well as increasing train length, train weight, and miles covered (partly by divestiture of branch lines), and by concentrating business in intermodal and fast freight segments. This trend should continue for a few years as the business changes, then level out for a number of years as efficiency gains become harder to achieve.

5.2 Fuel Conservation Measures

Among the measures that have been implemented to reduce railway fuel consumption are reductions in locomotive idle time, rail lubrication, and improved train handling, dispatching, and scheduling. A new combination of technologies called advanced train control systems (ATCS) holds great potential to reduce fuel consumption and increase operating efficiency. These measures are discussed below.

Reduced idle periods - Since the energy crises of 1974 and 1979, nearly all railroads have adopted formal policies to minimize locomotive idling, generally by requiring that locomotives be shut down whenever the temperature is above 45 °F, and the locomotive is not expected to be used for at least two hours. All of the California railroads have stated that they have idling reduction policies in place. Despite these stated policies, however, long idling periods are common. The Booz-Allen data from 1987-88 on locomotive duty cycles showed substantial periods of idling, totaling about 20,000 gallons of wasted fuel per locomotive per year. The duty cycles from the Amtrak *Capitols* show a surprising amount of idle time, considering that the data were taken in the warm months and the locomotives were shut down at night. Even in California, the temperature dips below 45 °F quite often. If the Booz-Allen data are representative, and the winter temperatures are low often enough, the potential for further reduction in emissions and fuel consumption through reduced idling is significant.

A number of obstacles to reducing locomotive idling exist. Locomotive engines were not designed to be turned off frequently. Cooling fans and turbocharger oil circulators may be needed to protect against overheating the turbocharger bearings if the engine is shut down immediately after heavy use. Coolant leaks into the cylinders and crankcases of stopped engines, because of the engine's mechanical design. Because of the danger of engine damage if glycol coolants leaked into the oil, plain water is used instead. Prolonged exposure to subfreezing temperatures when shut down could therefore damage the engine. In some cases, engine idling may be required in order to maintain air

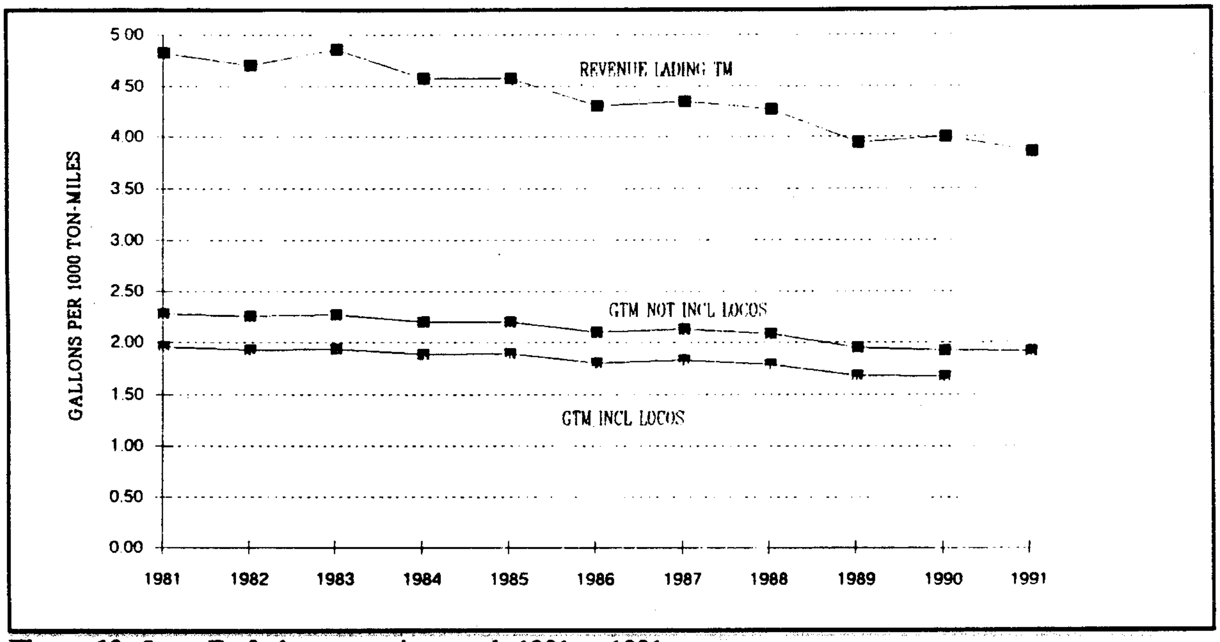

Figure 10: Santa Fe fuel consumption trend, 1981 to 1991.

pressure for train brake lines, and to keep locomotive batteries charged. Starting systems are not robust enough for frequent starts, especially if batteries are not replaced in good time, and the low compression ratio makes locomotive engines difficult to start at temperatures below 50 °F. A lengthy start-up procedure is required, and there is some danger (especially with engines in poor condition) that the engine may not start at all. Operational staff are therefore likely to resist a shutdown policy, and can easily sabotage such a requirement by (e.g.) spreading out work so that the engine is never "expected" to be idle for as long as two hours, or by simply ignoring it. These possibilities point up the need for effective monitoring and enforcement, both by the railroad management and by the ARB.

One effective approach to reduce excessive idling would be to convert switch and local-service locomotives to use smaller, high-speed diesel engines, as discussed in Chapter 8. These engines can readily be shut down and restarted, even in sub-freezing weather. The same is also true of larger engines such as the Caterpillar 3600 series, which could be retrofit into line-haul locomotives. On all locomotives, proper maintenance of engines, batteries, and starting systems can increase the reliability of restarts, and various cold starting aids are available to assist restarting under cold conditions. An electric coolant heating system is available to guard against freeze damage during prolonged shutdowns in cold weather. Another very promising possibility would be the use of a small auxiliary diesel engine, which could be left running in place of the main engine to maintain battery charge and air pressure, and to circulate coolant and lubricating oil. Waste heat from the auxiliary engine cooling jacket and the exhaust could be used to maintain oil and coolant temperatures in the main engine at acceptable levels. Unlike electric coolant heaters, this system does not require an external power source and hence can be used at remote locations. Although such a small engine would also produce emissions, these would be much less than those of the large-bore diesel engines.

Rail lubrication - By reducing the work required to move the train, rail lubrication reduces the amount of fuel consumed, and thus the emissions. Lubricant can be applied by locomotive-mounted devices, wayside (track mounted) systems, or systems mounted on separate hi-rail vehicles. Wayside lubricators have been used to reduce wear in curved sections of track. These systems are estimated to give a 3% energy savings over dry rail. Use of locomotive-mounted lubricators have been shown to yield an additional 5.5% savings over wayside lubricators when properly installed and operated (Peters and Reiff, 1989). The lower effectiveness of the wayside lubricators is partly due to the applied lubricant being used up and wiped off as the number of trains passing over the lubricated section increases. Every train using locomotive-mounted lubricators sees the maximum possible benefit of their use.

More than 3800 locomotive mounted lubricators had been installed nationwide as of 1989, resulting in a total savings of about $100 million after taxes (Gudiness; 1989). It has been shown that the economic benefits of wheel/rail lubrication far exceed the costs of purchasing and maintaining the lubricator systems. Despite these benefits, however, locomotive-mounted rail lubricators are not yet in universal use. SP has equipped 120 locomotives with lubricators, but *none of these lubricators are presently being used*. SP does have a number of curved and tangent rail lubricators installed, but states that it is concerned that depositing petroleum products (grease) on the exposed rails may be a violation of environmental regulations (Harstad, 1992)[24]. This seems improbable to us, and even if it were a problem, use of non-petroleum grease would still be possible. It is clear that the potential for fuel conservation has not been sufficient to motivate the railroad to find a solution in this case.

Improved Train Handling - The fuel economy realized by a consist or a single locomotive on a run is highly dependent on the actions and hence the skills of the engineer(s) running that consist. This has been documented; over 40% difference in fuel consumption can be observed between two operating styles on the same run (AAR, 1981). Up to 13% increase in efficiency has been observed depending on use of power braking, dynamic braking, or throttle modulation, or some combination thereof, used to slow the train. If the engineer misjudges an approach to a hill or does not properly calculate the weight balance of his train he may find himself applying full power at very slow speeds just to get over the hill. This wastes fuel and damages traction equipment. The industry provides high quality and quantity of training for its operators, but this training has traditionally focussed on safety rather than efficiency. Once out in the field it is difficult to control how efficiently trains are operated, and the engineers themselves have limited knowledge of efficient operating practices and little reason to care about fuel consumption.

Significant improvements in train handling will likely require improvements in monitoring and oversight of operator performance in order to improve feedback both to the operators themselves and to their supervisors. The most practical approach for providing such feedback would probably be via an advanced train control system (ATCS). Using a most general description, ATCS is a multi-layered, microprocessor based system designed to interface between the locomotives in the field and the railroad's central office or offices. The system is primarily designed to increase the global efficiency of railroad operations, and has attractive side-benefits both for reducing fuel consumption and for enhanced monitoring of emissions.

Improved dispatching and scheduling - Efficient locomotive dispatching can ensure that every train leaves the yard with the right amount and type of power for best efficiency, and that locomotives do not spend long periods idling within the yard or waiting for service, but are rapidly sent back out into revenue service again. Inefficient dispatching practices include sending backups in case one fails in use, and tying up an excessive number of idling units. These practices cost both fuel and money for maintenance, and result in an inefficient use of the capital embodied in the locomotive.

Train scheduling also plays a role in fuel consumption. "Hurry-up and wait" operation consumes more fuel than steady, slower running. Where it is necessary to schedule two trains to pass at a given point, proper scheduling can eliminate the need for one (and sometimes both) to stop. Central operations centers are one modern tool that railroads use to control this movement. To optimize these and similar efficiencies within the context of present signalling and train control systems is difficult, however. For this reason, as well as many others, interest in ATCS has been increasing rapidly.

ATCS - Advanced train control systems could make possible significant improvements in railroad operational efficiency, reducing fuel consumption, increasing equipment utilization, and reducing costs. The most basic component of ATCS is a data communications system which transfers information between trains and rail operations control centers. The locomotives communicate with wayside base stations. The base stations transmit to and from the company's network via microwaves, phone lines, buried cable or fiber optics, or any combination thereof. Each locomotive is equipped with a train control computer, and sensors to pick up speed, throttle, and brake settings, levels of consumables, alternator voltage and current, pressures, temperatures, coupler forces, and other variables. An on-board display is provided.

A train location system identifies locomotive positions anywhere in the railroad network. The system employs track mounted transponders, and can be enhanced with GPS (Global Positioning Satellite), providing each locomotive's position within 60 feet. Rail operations control computers continuously monitor locomotive positions, speeds, and performance. Computer databases retain route topography, train car allocation, train weight balance, and other pertinent data. The information is analyzed automatically and the results displayed for dispatchers and relayed to engineers. The most efficient train speeds to get over hills and meet other trains at sidings are displayed or optionally used in a command/control scheme (specific to the railroad that is using it).

Locomotive health and fuel consumption can be monitored continuously at network control, allowing mechanical departments to make timely repair and maintenance decisions and enhancing locomotive reliability. Filter clogging due to dirt or water can be discovered and flagged as it is happening, so that locomotives can be pulled out of service for maintenance when needed. Locomotive dispatching can be largely automated, with the computer selecting the units to be dispatched with each train for best efficiency and locomotive utilization. Other parts of railroad operation improved with ATCS include: (1) advanced automatic freight car allocation, (2) automatic equipment identification, to verify train consists at specific locations or routes, (3) train scheduling, (4) crew scheduling, to plan crew's work assignments, (5) freight car reservations and scheduling, to reserve cars and make schedules for customers, and (6) train signalling (*Railway Age*, 1991a).

Discussions with freight railroads have uncovered little outward interest in ATCS, but the extensive discussion of ATCS in trade journals suggests substantial behind-the-scenes interest. A joint project between Rockwell and Burlington Northern intends to implement Rockwell ARES (Advanced Railroad Electronics System) in Minnesota. The larger railroads are already using advanced technology for work order reporting and freight car reservations and scheduling.

Because of the risk and expense, participating railways are taking a subsystem approach, installing useful parts of the ATCS system and developing them slowly. Basic computer, sensor, and data radio installation would cost around $30,000 per locomotive. A full ATCS system would cost an additional $45,000 per locomotive plus $3 million for a 70 base station transmission network, assuming low-volume production (Morgan, 1991). For continuous coverage, a base station is needed at least every 60 miles, so that a 70 base-station network should more than suffice to cover California. Complete conversion to ATCS in California would therefore cost about 47 million dollars for locomotive equipment, and 9 million dollars for three base networks - one each for the ATSF, SP, and UP (not including the costs of the dedicated California fleet, discussed in Chapter 4). These costs would be paid back in improved fuel efficiency, lower operating costs, and better locomotive utilization. Efficiency gains are expected due to reduced locomotive time in the shop, increased unit availability, prevention of road failures, reduced train idle time, efficient train speeds, and optimized locomotive-to-train allocation. Union Pacific has said that locomotive health and performance monitoring could result in a 1 - 2% gain in locomotive availability, which translates to $30 million annual savings (*Progressive Railroading*, 1990). Unpublished information (confidential remarks of industry insiders) suggest total operating cost reductions as high as 30%. Half that would be many times the cost of ATCS. If the annual fuel consumed by locomotives in the six

California air basins is 141.5 million gallons (Booz-Allen, 1991), diesel fuel is $.70/gallon, and the fuel saved by using ATCS technology is a conservative 5%, the total direct savings to the industry would be 4.5 million dollars per year in fuel alone. The savings would be even greater if the technology were applicable to all California traffic.

Another important advantage of ATCS is that it would allow effective monitoring of locomotive operating practices, usage, and total emissions in California. The ATCS locomotive monitoring system would be capable of reporting the exact operating notch, fuel consumption rate, and position of every locomotive operating in California. By combining the operating notch data with stored emission measurements for each notch (updated through annual or bi-annual emission tests), a very good approximation of actual emissions could be obtained. Any deterioration in engine performance that could affect the notch-specific emission factors could also be detected, through the locomotive health monitoring system. The ARB could require, by regulation, that the railroads deliver such data on computer storage media (e.g. on a monthly basis, to make sure the data are current) - thus providing the equivalent of continuous emission monitoring, at very little incremental cost. Such monitoring would be essential if the ARB were to implement any form of "bubble" regulation for locomotive emission. It would also enhance the potential for enforcing command-and-control measures, especially such difficult-to-enforce measures as idling limitations and train-handling requirements, without creating excessive paperwork or administrative problems. This is not to say that ATCS is a prerequisite for locomotive monitoring, simply that monitoring is an extra to the benefits that the railroads would have.

5.3 Cost-effectiveness

Measures to improve locomotive fuel efficiency and the overall efficiency of railroad operations should result in a net reduction in annualized costs, implying negative cost-effectiveness. Thus, conventional measures of cost-effectiveness do not apply. However, if railroads were to choose to invest in these measures beyond that which returns fuel savings, in order to comply with an emission "bubble" law, then the costs would be positive and cost-effectiveness could be evaluated. It is not now possible to do this since there is not enough data or information that demonstrates the associated costs.

5.4 Regulatory Feasibility

Drafting and enforcement of command-and-control regulations for railroad operating practices are likely to prove complex and cumbersome. Such regulations might require many exceptions and special provisions to deal with the many real-life complexities of railroad operations. Effective enforcement of any regulatory design could be very difficult and burdensome to both regulators and the railroads, unless carried out by means of real-time monitoring such as with ATCS, as discussed above. The problems and administrative burden potentially involved in enforcing command and control regulations in this area strongly suggest that a "bubble" approach - mandating a given percentage reduction in emission, while leaving the details of how it is to be achieved to the railroads - would be preferable for both parties. The cost of fuel alone is some incentive, although apparently not always enough incentive, for the railroads to reduce their fuel consumption. Whatever the incentive, the technology is available for railroads to improve their efficiency.

5.5 Affordability

None of the fuel-conserving measures considered would involve major capital expenditures, except for full ATCS. All, especially the ATCS, would produce savings in operating costs. Therefore, affordability should not pose a significant problem.

5.6 Impact On Railroad Operations

Command-and-control regulation of operating practices could have a significant impact on railroad operations. Such regulations would be expected to reduce flexibility and increase costs. If ATCS were not used, such regulations might be difficult to enforce. The use of ATCS for its intended purpose of allowing the railroad to monitor and control its own operations should have a major beneficial effect overall, and would tend to reduce the adverse impact even of strict command-and-control regulations.

6. DIESEL FUEL MODIFICATIONS

Modifications to diesel fuel may be cost-effective for controlling emissions under some circumstances. The diesel fuel properties considered to have the greatest effects on emission are the sulfur content, aromatic hydrocarbon content, and the distillation properties - especially the 90% boiling point and the end point. Sulfur in diesel fuel contributes to SO_2 and particulate emissions, as well as increasing engine wear and lubricant deterioration. Normal diesel fuel sulfur content in the U.S. is about 0.2 to 0.5% by weight. To reduce SO_2 and particulate emissions, the ARB has limited the sulfur content of diesel fuel sold for highway use in the South Coast AQMD to 0.05% by weight for some time, and recently extended this requirement to the remainder of the state, starting in 1993. The same limitation applied to highway diesel fuel nationwide starting October, 1993.

6.1 Fuel Composition Effects

The aromatic hydrocarbon content is closely related to the ignition quality of diesel fuel, as measured by the cetane number. Reducing the aromatic content or increasing the cetane number will tend to reduce particulate, NOx, HC, and noise emissions. The typical aromatic content at present is about 30% by volume for diesel #2, and less for diesel #1. In order to reduce diesel NOx and particulate emissions, the ARB has adopted regulations that will limit diesel fuel sold for highway use in California to 10% aromatics by volume, unless the refiner can show that it is achieving the same emission benefits through other changes. The latter provision has prompted a great deal of research into possible emission-reducing additives for diesel fuel, and some promising results have recently been reported in literature.

There is also some evidence that the fuel volatility can affect emissions. High 90% boiling points or end points, in particular, are suspected of increasing particulate emission; conversely, a very light fuel (such as diesel #1) may reduce particulates and NOx. The extent and importance of these effects in locomotive engines are uncertain, however.

From considerations of fuel availability and emission effects, we defined three potential fuel specifications for locomotive diesel fuel. First, locomotives might be required to use fuel having no more than 0.05% sulfur by weight. Since highway vehicles throughout the U.S. were required to use this fuel starting October 1, 1993, it should be readily available. Low sulfur fuel is already required for highway vehicles in California, and in our preliminary discussions with the railroads, they have indicated that they are already using this fuel in many cases. This is primarily for reasons of availability - the low-sulfur fuel is available through petroleum product pipelines, which reduces the cost of handling. The savings through greater availability apparently offset the higher refining cost of this fuel compared to high-sulfur diesel, which we estimate at about two cents per gallon.

A second alternative would be to require locomotives to use low-aromatic, low-sulfur fuel meeting California 1993 specifications. This would probably help to further reduce particulates compared to low-sulfur fuel alone, and would also help to reduce NOx emission. The benefits of the low-aromatic fuel appear to be especially pronounced with retarded injection timing. For example, testing at SwRI (Markworth et al., 1991) showed NOx reductions of 10% in an EMD engine and 17% in a GE engine with the use of low-sulfur, low-aromatic diesel fuel at 4° injection timing retard. The lower density of the low-aromatic fuel results in a significant 3.5% energy per gallon penalty, however.

6.2 Cost-effectiveness

Table 19 shows a cost-effectiveness analysis for the use of low-aromatic fuel in local and switcher locomotive diesels. (This fuel would also be low-sulfur, but that characteristic would not have any affect on NOx). The low-aromatic fuel was assumed to reduce NOx emission 10%, at the cost of a 3.5% increase in fuel consumption due to the lower energy content. The cost of the fuel was assumed to be 10 cents per gallon higher than the present fuel, resulting in an additional cost of about $13,000 and $7,000 per year for the local and switcher locomotives, respectively. The resulting cost-effectiveness is about $5,500 per ton for the local application and about $4,300 per ton for the switcher application.

Table 19: Cost-effectiveness of low-aromatic fuel for local/switcher NOx reduction.

	EMD SD40-2/Local		EMD GP38-2/Switcher	
	Baseline	Low-Aromatic Fuel	Baseline	Low-Aromatic Fuel
Fuel cons. penalty		3.5%		3.5%
Fuel cons. (gal/yr)	104,135	107,780	53,337	55,204
Fuel cost ($/gal)	0.70	0.80	0.70	0.80
Added fuel cost		$13,329		$6,827
NOx emissions (ton/yr)	24.0	21.6	15.9	14.3
Cost-effectiveness ($/ton)		5,552		4,267

Table 20 is the same analysis for the three high-power locomotives on the line-haul duty cycle. Here the fuel penalties range from $33,000 to $38,000 per year. The cost-effec-

Table 20: Cost-effectiveness of low-aromatic fuel for line-haul NOx reduction.

	EMD GP60		GE B40-8		EMD SD40-2	
	Baseline	Low-Aromatic Fuel	Baseline	Low-Aromatic Fuel	Baseline	Low-Aromatic Fuel
Fuel cons. penalty		3.5%		3.5%		3.5%
Fuel cons. (gal/yr)	297,490	307,902	294,296	304,596	259,440	268,521
Fuel cost ($/gal)	0.70	0.80	0.70	0.80	0.70	0.80
Added fuel cost		$38,079		$37,670		$33,208
NOx emissions (ton/yr)	80.0	72.0	81.3	73.2	58.1	52.3
Cost-effectiveness ($/ton)		4,759		4,634		5,714

tiveness is between $4,800 and $5,700 per ton. Although competitive with other NOx control measures that have been adopted in California, these costs are significantly higher than for engine modifications or other hardware-type measures to reduce locomotive NOx emission, as the ultimate reduction is low.

6.3 Regulatory Feasibility

Enforcement of railroad fuel regulations, at least for fuel dispensed in California, should pose no major problems. The enforcement process would be similar to the existing process for highway diesel fuel. ARB inspectors could analyze fuel samples at refueling depots to confirm compliance. Regulations limiting the composition of fuel *burned* in California by line-haul locomotives that might have refueled outside the state would be somewhat more complicated, as it would be necessary to account for the possible effects of mixing the remaining non-California fuel in the tanks with California fuel.

6.4 Affordability

A requirement to use low-sulfur, low-aromatic fuel would increase railroad operating costs substantially, but the operating costs of trucking firms - their major competition - would increase even more. Trucking uses two to nine times as much fuel per ton-mile as rail transportation (Abacus Technology, 1991). Therefore, uniform application of fuel quality requirements should improve the competitive position of the railroads. (Of course, applying fuel quality specifications to trucks but not to railroads would improve the position even more. Depending on the cross-price elasticity of demand, and the railroad's response, this could possibly result in a net reduction in emissions, since the lower costs of the railroads could enable them to capture a larger share of the freight market.) The additional cost of running line-haul, local, and switcher locomotives on low-sulfur, low-aromatic fuel is estimated at 19 to 22 million, 3.1 million, and 1.9 million dollars per year, respectively.

6.5 Impact On Railroad Operations

A requirement to use low-sulfur, low-aromatic fuel in California should have little impact on railroad operations, unless it were extended to apply to line-haul locomotives refueling outside the state. In the latter case, refueling depots could be required to separate fuel supplies for locomotives destined for California from those for other destinations. This would impact both refueling operations and dispatching flexibility - how severely would have to be determined.

6.6 Implementation Schedule

Implementation of clean diesel fuels would depend entirely on the abilities of refineries to make the necessary changes, since there are no adverse locomotive effects. Since the question is largely that of volume, then the requirement could be introduced in stages, leading to full implementation in, for example, two years.

7. DIESEL ENGINE MODIFICATIONS

The most elegant approach to diesel emission control is to prevent the pollutants from being emitted from the cylinder in the first place. Pollutant formation and destruction in the cylinder are determined by the specific course of the diesel combustion process. Modifying this process to minimize pollution involves a complex multi-dimensional tradeoff between NOx, HC, and PM emissions, fuel economy, power output, smoke, cold-start ability, cost, and many other considerations. These modifications are most readily incorporated in new engines at the design stage, and this has been the approach used for other heavy-duty diesel engines to date. However, turnover of locomotives is so slow that limiting the modifications to new engines would produce only very limited improvements within the next decade. In addition, the Clean Air Act amendments adopted by the U.S. Congress in 1990 explicitly pre-empt any state regulation of *new* locomotives or locomotive engines. Finally, a distinctive feature of the locomotive engine market is that manufacturers have regularly introduced "upgrade" kits, replacement parts that incorporate design improvements, making available the results of the latest and most advanced technology in a form which can be retrofit to earlier engine models. Thus, in the case of locomotives, it makes considerable sense to consider retrofitting advanced diesel control technology to existing engines, as well as or instead of requiring it to be installed on new locomotives.

7.1 Emission Control Options

The typical locomotive engine is designed to undergo several overhauls before total replacement. The first overhaul is generally at 5 to 8 years service, the second overhaul is at 10 to 16 years, and then the rebuild of the entire locomotive, including the engine, takes place at 15 to 24 years[25]. Depending on the unit's condition and current economics, the owner may choose to replace the locomotive rather than rebuild it at this latter stage. Engine overhaul frequently includes upgrading the engine technology as well. Entire engine power assemblies (cylinder, cylinder head, piston, and connecting rod) can be unbolted and replaced with new parts incorporating the latest technology, at a cost of about $3,000 per cylinder, or $48,000 for a 16-cylinder engine (ATSF, 1992). Upgrading other components, such as the turbocharger, governor, and camshaft, would bring the total cost of a complete overhaul and emission upgrade to about $175-225,000, including cost overruns and labor (ATSF, 1992). This is far less than the $400,000 cost of a new engine.

The imposition of strict emission controls for on-highway truck engines has resulted in rapid progress in the understanding of diesel combustion and pollutant formation. The resulting technological advances have reduced engine-out emission from new on-highway diesels by a factor of two or more since the early 1980s. Most on-highway engine manufacturers have followed a broadly similar approach to in-cylinder control. This typical approach includes the following major elements:

- Minimize parasitic HC and PM emissions (those not directly related to the combustion process) by minimizing injection nozzle sac volume and reducing oil consumption to the extent possible;

- Reduce PM emission at constant NOx by refining the turbo-charger/engine match and improving engine "breathing" characteristics. Many manufacturers are also experimenting with variable-geometry turbochargers to improve the turbocharger match over a wider speed range;

- Reduce PM and NOx by cooling the compressed charge air as much as possible, via air-air or low-temperature air-water aftercoolers;

- Further reduce NOx to meet regulatory targets by severely retarding fuel injection timing over most of the speed/load range. Minimize the adverse effects of retarded timing on smoke, starting, and light-load HC emission via a flexible timing system to advance the timing under these conditions;

- Recover the PM increase due to retarded timing by increasing the fuel injection pressure and injection rate;

- Improve air utilization (and reduce PM emission) by minimizing parasitic volumes formed by piston/cylinder head clearances and piston top land (space between top ring and top of piston).

- Optimize in-cylinder air motion through changes in combustion chamber geometry and intake air swirl to provide adequate mixing at low speeds (to minimize smoke and PM) without over-rapid mixing at high speeds (which would increase HC and NOx); and

- Control smoke and particulate emissions in full-power operation and transient accelerations through improved governor curve shaping and transient smoke limiting (generally through electronic governor controls).

With the expected advent of federal emission standards for new locomotives in the latter part of the 1990s, it is to be expected that many of these emission control techniques will be applied to new locomotive engines as well. AAR spokesmen have indicated that they expect the forthcoming federal standards to be as difficult to attain as the U.S. 1991 standards for heavy-duty truck engines. The U.S. standards limit NOx emission to 5.0 g/BHP-hr and particulate emission to 0.25 g/BHP-hr. Prototype EMD engines had already achieved NOx emission levels in the 6 to 7 g/BHP-hr range several years ago, using a combination of severely retarded injection timing and higher injection pressure. It is therefore reasonable to expect that manufacturers could meet federal standards similar to those for on-highway trucks within five years. Once the technology is developed, it should be possible to retrofit it to existing engines as part of the overhaul process.

In the interim period before technologies meeting the new federal standards are developed, it would still be possible to reduce NOx emission significantly through engine modifications. For example, a combination of mildly retarded (4°) injection timing and enhanced aftercooling was shown to reduce NOx emissions from both an EMD and a GE engine by 20% (to 8.0 and 9.2 g/BHP-hr, respectively), at a cost in fuel economy of 0.4% for the EMD and 1.2% for the GE engine (Markworth et al., 1991). Particulate emissions also increased due to the retarded timing. Retarding injection timing further produced even greater NOx reductions, but particulate emissions and fuel consumption also increased significantly. In earlier work with another EMD engine in marine service (Peirson et al, 1987), NOx emissions were decreased from an estimated 13.9 to 8.3 g/BHP-hr by retarding injection timing 4°, while low-temperature aftercooling gave a further reduction of 0.7 to 1.6 g/BHP-hr, depending on load. Effects on fuel economy and particulate emissions were not measured during this study.

Retarded injection timing has been applied to the EMD F59PH locomotive models purchased for the Los Angeles area Metrolink system (Progressive Railroading, 1992). This produced a 20% NOx reduction from the unmodified version (Wright, 1992). EMD had plans to add aftercooling to a Metrolink locomotive for additional 10% NOx reduction (see Cost-effectiveness, below); that plan was canceled because the aftercooler would not fit in the existing locomotive easily. The AAR, in conjunction with SwRI, has studied retarded timing and found that 4 degree retard results in 23% NOx reduction with 60% PM increase and 1 to 2% fuel penalty (AAR, 1990). Other work has shown that retarding the timing 6 degrees on the roots-blown engines used in most switchers results in a 39% NOx reduction with only a 2.5% fuel consumption increase. The same retardation, along with other modifications to the engine and higher-rate injectors can give as much as 50% NOx reduction on turbocharged engines (Davis, 1986).

The results of Markworth et al. and Peirson et al. were obtained primarily by modifying the stock injection timing, with no changes made to the injectors themselves or to other parts of the engine. Experience in heavy-duty truck diesel engines shows that the adverse effects of retarding injection timing are due primarily to delaying the end of injection, and can largely be offset by increasing injection pressure (to reduce injection duration) and optimizing air motion within the cylinder. Other changes such as enhanced charge-air cooling, camshaft modifications, turbocharger modifications, changes in engine notch settings, and even piston ring modifications may also be needed in order to minimize NOx emissions with minimum impact on fuel economy or emission of other pollutants[26]. Such modifications should preferably be incorporated as part of an "engineered" retrofit package for specific engine and locomotive models. Such a package could be developed and marketed either by the original engine manufacturer, or by a third-party organization such as a locomotive rebuilder. Based on the data summarized above and the experience with heavy-duty truck diesel engines, we estimate that such a retrofit package could reduce NOx emission from existing turbocharged locomotive engines to about 7 g/BHP-hr, at a cost of no more than 4% in fuel economy. In the case of roots-blown switch engines, the potential benefits are less, and it would probably be most cost-effective simply to replace these with rebuilt locomotives incorporating smaller, high-speed engines equipped with emission controls.

7.2 Cost-effectiveness

There are data available which allow us to calculate the cost-effectiveness for a simple retarded timing case as well as to estimate a simple retarded timing plus improved aftercooling case. These data are from a recent study, sponsored by Caltrans, and performed and analyzed by SwRI (Fritz, 1992). An EMD 710G3A engine (in a F59PH, the same as the Metrolink passenger locomotives, cited above) and a GE 7FDLJ8 engine (in a Dash 8 B32PWH passenger locomotive) were measured for emissions and fuel consumption before and after the timing was retarded 4 degrees. These data and the Booz-Allen line-haul duty cycles were used to calculate the results shown in Table 21. The retarded timing reduces NOx more on the EMD than the GE, and the PM penalty is less severe on the EMD. There are HC and CO penalties with retarded timing, as expected, although the CO penalty is worse for the GE than the EMD. Fuel economy is about 1% worse for both makes[27]. The cost of changing the timing is estimated at $2000 per unit, mostly labor and locomotive down time, spread over 10 years at 8% discount rate. The cost-effectiveness is simply the cost of the extra fuel plus the annualized conversion cost divided by the tons of NOx reduced. The cost-effectiveness is apparently quite good, and if the reduction were applied to 633 in-state line-haul locomotives (as determined in Chapter 4), then the 6-basin annual NOx reduction would be roughly 11,000 tons per year (EMD and GE averaged).

Test data with retarded timing plus improved aftercooling were not available at the time EF&EE prepared this report, but the further NOx reduction due to improved aftercooling has been estimated to be 10% by those planning the Metrolink low-emission demonstration projects. The right-most column of Table 21 represents the NOx reduction estimates for engines with retarded timing and improved aftercooling based on this estimated 10% reduction from the retarded timing case (only NOx is calculated). Fuel economy is assumed to be the same as the baseline case, since aftercooling tends to improve fuel economy. Thirty thousand dollars per locomotive is added for the one-time only conversion (EF&EE estimate), annualized at 8% discount rate for 10 years. The resulting cost-effectiveness is still quite good, and the annual 6-basin emission reduction is about 15,000 tons (EMD and GE averaged).

Table 21: Cost-effectiveness of retarded timing and improved aftercooling in late-model locomotives.

	Baseline	4 degree retard	Retard + aftercooling
EMD GP60			
NOx (tons/year)	80.0	57.4	51.6
HC (tons/year)	2.2	2.3	n/a
CO (tons/year)	5.8	4.1	n/a
PM (tons/year)	0.1	0.1	n/a
Fuel (gals/year)	297,490	300,494	297,490
Fuel penalty (dollars/yr)		$2,103	$0
Conversion cost ($/yr)		$298	$4,471
Cost eff. ($/ton NOx)		**$106**	**$158**
GE 40B-8			
NOx (tons/year)	85.3	71.7	64.5
HC (tons/year)	4.4	4.5	n/a
CO (tons/year)	10.4	9.3	n/a
PM (tons/year)	1.5	1.6	n/a
Fuel (gals/year)	309,759	313,592	309,759
Fuel penalty (dollars/yr)		$2,683	$0
Conversion cost ($/yr)		$298	$4,471
Cost eff. ($/ton NOx)		**$220**	**$215**

Table 22 summarizes the estimated cost-effectiveness of an "engineered" retrofit package, such as might be developed in the next few years, in both line-haul and local-service applications, and uses the SD40-2 as the representative locomotive. Installation of the package, which might include new injectors, camshaft, pistons, and turbocharger, along with a separate-circuit aftercooler and retarded injection timing, is estimated to cost no more than $100-,000 per locomotive (over and above typical major overhaul costs), and to reduce NOx emission to 7.0 g/BHP-hr. This is equivalent to a 44% reduction from the present averages of roughly 12.5 g/BHP-hr for line-haul units, and a 48% reduction from the 13.5 g/BHP-hr average for units in local service. No credit was taken for extending the remaining useful life of the locomotive, or for reducing annual unscheduled maintenance costs, since it was assumed the overhaul was being performed anyway. The resulting cost-effectiveness values are $870 to $1,300 per ton of NOx for the line-haul units, and $1,100 to $2,600 per ton for the units in local service, indicating that this modification would be highly cost-effective. (Note that the line-haul cost-effectiveness values assume that the locomotive would be used entirely within California - i.e. a California-only fleet. If the railroads decided to operate these locomotives outside California part of the time, the costs per locomotive would be the same, but the emission reduction *in California* would be reduced, assuming that uncontrolled locomotives take their place, and thus the cost per ton would be higher). The railroads, to allow for decreased efficiency of utilization due to the need for switching power at the gateways, will need to purchase and maintain some extra locomotives in addition to a dedicated fleet. These costs are not included in the analysis.

Table 22: Cost-effectiveness of engine modifications and engine replacement for local and line-haul SD40-2 locomotives.

	Uncontrolled Baseline	Engineered retrofit package	Rebuilt to new EPA std.	Replace with new EPA-std. engine
SD40-2 Line-Haul Locomotive				
Capital cost ($)		$100,000	$150,000	$450,000
Useful life (yrs)		10	10	20
Annualized cost ($/yr)		$14,903	$22,354	$45,833
Fuel cons. penalty		4%	2%	0%
Ann. fuel cons.	259,440	269,818	264,629	259,440
Fuel cost/gallon	0.70	0.70	0.70	0.70
Fuel cost penalty/yr		$7,264	$3,632	$0
Total annualized cost		$22,167	$25,987	$45,833
Est. NOx g/BHP-hr	12.5	7.0	5.0	5.0
NOx emissions (tons/yr)	58.1	32.5	23.2	23.2
Cost-eff. ($/ton)		**867**	**745**	**1,314**
SD40-2 Local-Service Locomotive				
Capital cost ($)		$100,000	$150,000	$450,000
Useful life (yrs)		20	20	30
Annualized cost ($/yr)		$10,185	$15,278	$39,972
Fuel cons. penalty		4%	2%	0%
Ann. fuel cons.	104,135	108,301	106,218	104,135
Fuel cost/gallon	0.70	0.70	0.70	0.70
Fuel cost penalty/yr		2,916	1,458	0
Total annualized cost		$13,101	$16,736	$39,972
Est. NOx g/BHP-hr	13.5	7.0	5.0	5.0
NOx emissions (tons/yr)	24.0	12.4	8.9	8.9
Cost-eff. ($/ton)		**1,133**	**1,107**	**2,644**

Table 22 also summarizes the potential cost-effectiveness of retrofitting more sophisticated emission control technologies when those technologies are developed. It was assumed that EPA standards for new locomotives will require emission performance equivalent to 5 g/BHP-hr NOx. It was further assumed that - as is common with newly-developed locomotive engine technology at present - the emission control technology used in these new engines could be retrofit to existing engines as well. This was assumed to cost around $150,000 per engine at most, and to result in a fuel consumption penalty of at most 2%. As shown in Table 22, the cost-effectiveness of this measure would be even more attractive than that of the less-advanced retrofit package[28].

Although we consider it likely, it is by no means certain that engine manufacturers could or would make available the latest emission control technology in a form which could be retrofit to existing locomotive engines. Even if it not possible to fit the new technology to an old engine, however, it should be possible to substitute a new emission-controlled engine for the existing one. We assumed (conservatively) that a new engine would cost $450,000 installed, and would have no better fuel economy than the engine already in the locomotive. As shown in Table 22, even this extreme case results in attractive cost-effectiveness values.

7.3 Regulatory Feasibility

The federal pre-emption in the Clean Air Act prohibits the ARB or any other state agency from adopting or enforcing emission standards for new locomotives or locomotive engines. However, it does not prohibit California from requiring railroads to *use* engines meeting federal emission standards, once these go into effect. The question of whether California could adopt standards for in-use engines different from, or effective earlier than, the Federal new-engine standards will need to be addressed by the ARB legal staff.

Diesel engine modifications should present no special problems from an enforcement standpoint. Railroads could provide the ARB with a list of locomotives authorized to operate in California, along with technical data on the modification package and the results of emission testing. These could be verified by spot-checks. ARB inspectors could then check whether a given locomotive appeared on the list or not. Or, using the advanced monitoring and data collection technologies discussed earlier, the total emissions could be calculated from locomotive movement and emission performance data.

7.4 Affordability

The costs and affordability of these modifications would depend on the number of locomotives to be modified, and the costs of the modification package, but would be relatively moderate compared to some of the other measures under consideration. By the analysis in Chapter 4, we estimate that there are about 271 switchers and 235 local-service locomotives *active* in California on average. Although the number of line-haul locomotives that sometimes operate in California may be as high as two or three thousand, total gross ton-miles pulled in California is equivalent to about 586 locomotives operating *full-time* in the state. We estimated that a California-only line-haul fleet would need to include about 628 locomotives (including some allowance for decreased efficiency of utilization due to the need for switching power at the gateways). Total conversion costs, if all of these units were to be retrofit, would be about 63 million dollars. Local unit conversion adds another 24 million dollars for units in local service - costs which should be within the financial capabilities of the railroads.

7.5 Impact On Railroad Operations

Compared to other emission control techniques, modifications to the existing diesel engines would have relatively little impact on railroad operations, unless railroads chose to set up a separate California-only fleet. Potential impacts of these modifications could include slightly reduced power output, increased fuel consumption and changes in reliability. However, with sufficient engineering lead-time, it should be possible to configure a retrofit package such that it did not adversely affect power, fuel economy, or reliability, and could possibly have beneficial effects.

7.6 Implementation Schedule

Meetings with locomotive OEMs (Original Equipment Manufacturers) revealed that, other than a little research on retarded timing, very little has been done with reduced emissions. We were unable to uncover any data relating reliability to these engine modifications. EMD has done some research on increased injection pressure, but the program was stalled due to budget constraints. Likewise, data that relate maintenance costs to type of service, age and type of engines, and maintenance practices are scarce.

On the other hand, EMD has been willing to put retarded timing in the market with their F59PH models for Metrolink. Fuel consumption penalties are less of a concern to urban commuter operators, but as we have shown, the fuel penalty is not devastating.

In Chapter 8 of this report we show that at least one substitute (non-OEM) locomotive engine has significantly better emissions than the engine it would likely replace. This is an indication that the aftermarket power builders have a head start on the locomotive OEMs in reducing emissions, meaning that, at least in the lower power local and switcher market, short term emission reductions are possible. Also, the results from the retarded-timing Metrolink EMD F59PH indicate that immediate NOx reductions can be achieved with very little fuel or smoke penalty. Additional development required to give even better results without significant performance or emission penalties would likely take 2 to 4 more years.

8. REPLACEMENT AND REBUILDING OF DIESEL LOCOMOTIVES

As discussed in Chapter 7, EPA's future emission standards for new locomotives and locomotive engines are expected to resemble those for 1991 model year heavy-duty truck engines. Emissions from locomotives meeting such standards will be far lower than those from the present fleet. One potential approach to reducing emissions in California, therefore, would be to require the use of such new locomotives once they become available. Although such emission-controlled locomotives are not likely to be available until the late 1990s, it would be important to adopt appropriate regulations earlier, to allow the affected railroads to plan their capital acquisitions accordingly.

Although new locomotives incorporating effective emission controls are unlikely to be available from original equipment manufacturers until the late 1990s, rebuilt locomotives incorporating such controls could be available for switching and local service much earlier. Locomotives in these classes at present are generally very old, near or beyond the ends of their service lives, and equipped with obsolete and inefficient engines. Although power ratings in local service range up to 3000 hp, this power is seldom fully used, as documented in Chapter 3. Because of the difficulty and uncertainty in starting them, as well as the danger of freezing during cold weather due to their inability to use antifreeze, these engines spend a great deal of time idling. In Section 3.2, it was estimated that this idling wastes up to 20,000 gallons of fuel per locomotive per year.

Large, medium-speed engines are not the only choice for locomotive power, especially in switcher and local-service. A better choice may be the use of large, high-speed diesels such as the Caterpillar 3500, Cummins KTA, and Detroit Diesel 149 series engines. Although each has its own features, these engine series all share certain characteristics, including power ratings in the 1000 to 2000 hp range, the use of antifreeze/coolant, relative ease of starting even in cold weather, and demonstrated reliability in a wide range of demanding applications. Both the Caterpillar and the Detroit Diesel are now offered in remanufactured locomotives intended for local and switching use. Because the engine technology for each of these families has many features similar to those of heavy-duty truck engines (and because each is manufactured by a leading truck engine builder), it should be possible to incorporate levels of emission control similar to those required in trucks much more easily than in medium-speed locomotive engines. For example, all three engine series are now offered in versions with electronic governor control, and the Caterpillar and Detroit Diesel are both offered with electronic unit injectors allowing flexible control of fuel injection quantities and timing. These advanced technologies, originally developed to meet heavy-duty truck emission standards, allow emissions to be optimized at a considerably lower level than diesels with less flexible fuel systems.

8.1 Technical Issues and Cost-effectiveness

This section addresses the cost-effectiveness of locomotive replacement and/or remanufacturing as an emission control measure. Of course, the primary motivation to replace or refurbish a locomotive is not to reduce emissions, but rather to reduce operating costs and increase efficiency and reliability. These effects have proven difficult to capture in this analysis, which therefore probably overestimates the net costs of the replacement operation.

Yard or switcher locomotives - It is unlikely that a railroad would choose to purchase an "all-new" switcher, that is, a switcher designed and produced as new, for the reasons discussed in Section 2. It is generally not perceived as economical to pay over one million dollars for such equipment when \$50,000 to \$100,000 used equipment seems to satisfactorily accomplish the task. However, railroads may find efficiency and emission opportunities by rebuilding or replacing old switchers.

Compared to the older medium-speed engines found in switch locomotives, modern high-speed engines such as the Caterpillar 3516 or Detroit 16V-149 would have better fuel efficiency due to combustion chamber improvements, better part-load fuel control, turbocharging improvements, and electronic engine controls. (Modern medium-speed engines also have greatly improved fuel efficiency). The Caterpillar units have optional features designed exclusively for locomotives, such as electronic speed and load control units that incorporate wheel slip (adhesion control) and dynamic braking input. Oil economy would be improved substantially. Furthermore, this technology allows overnight shut down in 10 °F weather, along with easy, reliable starting - thus making prolonged idling unnecessary, with a consequent large savings in fuel and engine wear.

A surplus of old switchers means a boon for the locomotive rebuilding and parts industries. Locomotives can typically be rebuilt for 50 to 60 % of what they would cost if new. Many parts of the used locomotive, including the truck frames, the traction motors, and much of the body, can be effectively recycled, if the remanufacturer chooses to do so. Rebuilders overhaul the existing engine with upgrade kits, or install any powerplant specified by the customer. Other custom features can also be incorporated into the rebuild. Most rebuilders prefer to install the products of particular suppliers, but any one of the engine series discussed above, as well as traditional engines, could be installed in a rebuilt switcher. Switcher service is less demanding than line-haul service, so rebuilding of switchers (and locals) may not require as much sophisticated and expensive engineering.

Table 23: Cost-effectiveness of remanufacturing existing switchers and locals with new, low-emitting engines.

	EMD SD40-2		EMD GP38-2	
	Local cycle		Switcher cycle	
	Existing	Reman. (5 g/bhp-hr)	Existing	Reman. (5 g/bhp-hr)
Capital Cost ($)	-	$850,000	-	$700,000
Useful Life, Years	20	20	20	20
Annualized Cost @ 8%	-	$86,574	-	$71,297
Maintenance Cost Per Yr	$108,800	$87,040	$83,200	$66,560
Fuel Consumed (gals/yr)	104,135	83,308	53,337	42,669
Fuel Cost Per Gallon	$0.70	$0.70	$0.70	$0.70
Fuel Cost/Yr	$72,895	$58,316	$37,336	$29,868
Total Cost/Yr	$181,695	$231,930	$120,536	$167,725
NOx Emissions (tons)	24.0	11.3	15.9	5.9
NOx Reduction/yr (tons)		12.7		10.0
Cost Effectiveness ($/ton)		$3,960		$4,715

Table 23 gives rough estimates of the costs and cost-effectiveness of replacing existing switch and local locomotives with remanufactured units incorporating emission-controlled, high-speed diesel engines. The cost of the remanufactured switcher would be about $700,000, which is equivalent to $71,000 per year at 8% interest, for a theoretical 20 year lifetime (costs are from rebuilder's estimates). To be conservative, we have assumed that the locomotive being replaced could also have lasted 20 years more. Scheduled maintenance cost is expected to be the same for new or used units. Unscheduled maintenance costs, caused by aging wires, seals, and plumbing, are estimated to be 20% less on the new or remanufactured units, even though they would remain close to zero for the first 4 or 5 years of the machine's life.

As stated in Chapter 3, the typical California switch engine consumes about 53,000 gallons of fuel per year. Fuel consumption for the rebuilt locomotive could be as much as 6,000 gallons per year less, due to the reduced need for idling. Other efficiency improvements would also contribute to better fuel economy. Total annual cost is the sum of the annualized capital cost, maintenance, and fuel costs. As Table 23 shows, the total annualized cost of a remanufactured switcher would be around $47,000 more than the existing unit, due to the greater capital cost. However, this assumes that the existing unit would last another 20 years. Since, in reality, many older locomotives are near the end of their economic lives, the true economic costs would, in many cases, be much less.

NOx emissions for the existing locomotives were calculated in Chapter 3. Remanufactured locomotive NOx levels were estimated by scaling the Booz-Allen emission factors by the ratio of notch 8 before and after factors (for example, before/after, or 12.5 g per hp-hr/5 g per hp-hr). An actual low-emission diesel engine would probably have a fairly similar linear reduction across the load range. As shown in Table 23, with the 60% or so NOx reduction, the cost-effectiveness is $4,700/ton NOx reduced.

<u>Local service locomotives</u> - Replacing obsolete line-haul units in local service with remanufactured locomotives designed for this type of service should result in substantially higher productivity. Although the horsepower rating of such a unit might be less, modern wheel-slip control allows more effective use of the available horsepower, so that actual productivity would be the same or greater. Alternatively, a larger engine (such as the Caterpillar 3600) could be fitted to give equivalent horsepower to the existing units, if required and if the higher costs are justified. In either case, the effects of the more modern and efficient engine, the savings from being able to shut the unit down rather than leaving it idling, electric auxiliary drives, and greater reliability should result in lower operating costs.

The cost-effectiveness analysis in Table 23 gives a conservative estimate of the benefits of remanufacturing an existing local locomotive. Credit is taken only for the savings on fuel due to reduced idling, and to the (unscheduled) maintenance savings from a newer, more reliable unit. The other benefits of increased reliability, more effective utilization, etc. are not included. The cost of the remanufactured locomotive is assumed to be $850,000, giving an annualized capital cost of $87,000 at 8% interest and 20 years service life. The total cost per year is the sum of the annualized capital cost, the annual maintenance cost, and the annual fuel cost. NOx emissions for the existing engine are as estimated in Chapter 3; those for the remanufactured engine are based on quotes for a Caterpillar engine package. The resulting cost-effectiveness for locomotive replacement is $3,960 per ton of NOx reduced, which is competitive with other NOx control measures that are being required in California. No credit is taken in this analysis for the increased reliability and productivity that would be expected to result from the new-locomotive features such as on-

Table 24: Fuel consumption comparison, EMD 16-645E3 and CAT 3516 in switcher duty cycle.

FUEL COMPARISON (GP38-2 with CAT 3516)				
Throttle Notch	EMD Fuel Cons. (gal/hr)	EMD Weighted Fuel (gals/hr)	CAT Fuel Cons. (gal/hr)	CAT Weighted Fuel (gals/hr)
off	0	0.00	0	0.00
brake	19	0.00	6	0.00
idle	6	2.16	2	0.55
1	12	0.50	5	0.15
2	22	0.92	13	0.43
3	40	1.17	28	0.63
4	56	1.62	44	0.97
5	78	0.77	56	0.42
6	102	0.51	72	0.28
7	146	0.00	90	0.00
8	172	1.95	104	0.91
Total fuel, gals/year		53,337		33,543
Fuel economy improvement				37%

board diagnostics, advanced wheel-slip control, and higher maximum horsepower, or for the possibility that the existing locomotive would have to be replaced or remanufactured in any event. The resulting cost-effectiveness values are therefore highly conservative.

Line haul locomotives - Replacing an efficient, late model, line-haul locomotive such as the EMD SD60 or GE Dash 8 with a new low-emission unit was deemed uneconomic. New line-haul locomotives are very expensive, and already possess a great efficiency advantage over their predecessors. Therefore, the replacement scenario for line-haul locomotives was rejected, and no cost-effectiveness table for line-hauls was developed.

Replacement engine example - To estimate the fuel and emission benefits (or detriments) of substitute motive power we have taken data for the EMD 16-645E and the Caterpillar 3516 Locomotive version and calculated total fuel use and emissions. Table 24 shows the fuel consumption that was calculated using the results of a test conducted by Generation II locomotive rebuilders and Caterpillar. In that test, they ran an EMD GP38 with a Roots-blown 16-645E and another GP38 with a CAT 3516 on the same run. The Caterpillar has 300 less horsepower than the EMD but produces the same or better tractive effort with use of electronic wheel slip controls. Over their test on a 28 mile iron-ore line, they achieved about 21% better fuel economy with the Caterpillar-equipped locomotive. Using the same notch-specific fuel usage data, but over the California switcher service duty cycle discussed in Chapter 3, including a reduction in overall idling time, we calculated a 37% improvement. For the Caterpillar-equipped case, we have decreased idling by half and increased the off time by the same amount, to reflect the Caterpillar's ease of shutdown and start-up. This gives the Caterpillar an extra advantage in both fuel and emissions. The idling reduction by itself is responsible for some 7 to 9% of the total fuel consumption. The local duty cycle fuel consumption (not shown) was reduced by 40%.

Emission comparisons were also made for a hypothetical locomotive equipped with a Caterpillar 3516 TA diesel engine at standard timing and with 3.75 degrees of timing retard. Baseline EMD numbers came from the Scott Labs report (Conlon, 1988). A summary of the emission reductions are given in Table 25. The retarded-timing CAT-equipped local achieves an impressive 67% NOx reduction, with no change in HC emission and a slight increase in CO emission. There would probably be a fuel penalty for the retarded timing on the Caterpillar, but those data were not available.

8.2 Regulatory Feasibility

As noted earlier, the federal pre-emption in the Clean Air Act prohibits the ARB or any other state agency from adopting or enforcing emission standards for new locomotives or locomotive engines, but it does not prohibit California from requiring railroads to *use* engines meeting federal emission standards, once these go into effect. Enforcement of such a requirement would be straightforward. As in the case of engine modifications, railroads would provide the ARB with a list of locomotives authorized to operate in California, along with the manufacturer's certification that these locomotives meet EPA standards. ARB inspectors could then check whether a given locomotive appeared on the list or not.

Table 25: Emission output; replacing EMD engine with CAT engine, in yard and local duty cycles.

	Baseline 16-645E	3516 w/ standard timing	3516 w/ 3.75 degree retard
GP38-2 Yard			
NOx (tons/yr)	15.9	9.3	5.2
HC (tons/yr)	0.8	0.7	0.9
CO (tons/yr)	2.1	2.7	3.0
Fuel (gals/yr)	53,337	33,543	N/A
GP38-2 Local			
NOx (tons/yr)	24.0	14.6	8.9
HC (tons/yr)	1.8	0.9	1.1
CO (tons/yr)	4.5	3.2	3.6
Fuel (gals/yr)	104,135	56,757	N/A

8.3 Affordability

Replacing the equivalent of the entire California locomotive fleet with remanufactured units would involve a major capital expenditure. Two-hundred and thirty-five remanufactured local units at $850,000 and 271 switchers at $700,000 each would bring the total to 390 million dollars. It is questionable whether the railroads could raise capital on this scale, even if the purchases were spread out over many years. On the other hand, replacement may be a viable option in pollution intensive applications and (potentially) highly regulated locations, such as dedicated local and switcher assignments in densely populated urban areas. Partial fleet conversion could be part of a multi-option strategy to meet emission caps.

8.4 Impact On Railroad Operations

Replacing existing local and switcher locomotives with remanufactured units should have a beneficial effect on railroad operations, due to the greater productivity and reliability these units offer, and since these units stay within California all the time. If only remanufactured *line-haul* locomotives were allowed in California, however, it could disrupt operations, owing to the need to change locomotives at gateway points.

9. SELECTIVE CATALYTIC REDUCTION

A number of aftertreatment NOx control technologies have been developed for use in stationary applications, but the only one that appears very promising for locomotive use at present is Selective Catalytic Reduction, or SCR. Because they operate at lean air-fuel ratios, diesel engines cannot use three-way non-selective catalytic converters for NOx control. The only aftertreatment option for NOx control is therefore SCR. Unlike the non-selective catalytic reduction of the three-way catalyst, SCR does not require rich or stoichiometric air-fuel ratios, making it suitable for use with diesel and other lean-burn engines. In this approach, the required chemical reduction potential is supplied by a separate reductant material. This is usually ammonia, but urea can also be used. Selective catalytic converter systems based on precious metals, on non-precious metal-oxide (base metal) catalysts, and on zeolite catalysts are now being offered commercially for stationary diesel engines, and a number have been installed - mostly in Europe. SCR systems using precious-metal catalysts can also function as catalytic converters, and can therefore control both NOx and particulate emissions. They can also function at lower temperatures than the competing types, but they are sensitive to sulfur in the fuel and have a narrow temperature range. The SCR design evaluated in this report uses a combination of base metal and precious metal catalysts, applied to a metal rather than ceramic substrate.

There is another aftertreatment technology that deserves mention, though it does not appear ready for mobile applications. This is the Cummins NOXTech system, which is based on a selective non-catalytic process. The reductant material is cyanuric acid, HNCO, which is made from urea. It is stored as a solid and transported to the reaction chamber[29] with compressed air. An auxiliary fuel supply is used to heat the exhaust gas in the reaction chamber to 1200 °C (2200 °F). At this temperature, the cyanuric acid sublimates to a gas and disassociates to isocyanate. This compound then reacts with the NOx in the exhaust to form N_2, CO_2, and H_2O. The extremely high temperature also serves to oxidize the unburned hydrocarbons and particulate matter in the exhaust stream. A sophisticated control system monitors temperatures and delivers only enough cyanuric acid to react with the NOx. The advantages of this system are absence of catalyst, the ability to handle all exhaust pollutants simultaneously, and the ease of cyanuric acid handling. The disadvantages are the high fuel costs to heat the exhaust, the difficulties of engineering a high temperature reaction chamber - especially for mobile applications -

and the system bulk. A NOXTech system is operating in a diesel powered generation system in Minneapolis (*Diesel Progress*, 1992).

9.1 SCR Technology

SCR is not a particularly complex technology, but it is rather expensive, owing to the kinds and amounts of materials needed to construct and operate it. SCR has never been applied in North American freight locomotives, but it has been applied in enough mobile diesel applications to make the North American locomotive a logical next step. Once properly engineered and developed, SCR units could be installed by any company that repairs or rebuilds locomotives.

How SCR works - SCR eliminates NOx through a catalyst-promoted reaction between ammonia (NH_3) or urea (H_2NCONH_2) with NOx to form harmless N_2 and water. Ammonia can be supplied in aqueous solution or anhydrous. Urea is a solid which is dissolved in water for transfer to the reaction chamber. Production units using ammonia and urea are operating successfully on offshore oil platforms, stationary reciprocating and turbine power plants, diesel motorships and boats, and in a rail grinder designed for underground operation in Switzerland. SCR has been the most effective method of controlling emissions in stationary installations since the mid-1970's, with a potential effectiveness in excess of 80%.

Exhaust temperature requirements - Efficient operation of SCR systems requires that the exhaust temperature be within the normal SCR operating range. For common base metal catalysts, this range is 250 to 450 °C (482 to 842 °F). Zeolite catalysts can tolerate higher temperatures than those using metals. Figure 11 shows the typical relationship between temperature and efficiency (EPRI, 1990), with efficiency dropping off at the high and low end of the range. This temperature range corresponds to roughly notch 4 and higher power settings in present 2-stroke diesel locomotives - settings which are responsible for more than 75% of total emissions from line-haul locomotives. Four-stroke GE locomotives have higher exhaust temperatures in the lower notches, so that SCR would be effective over an even wider range. Table 26 shows the exhaust temperatures for representative EMD and GE locomotives.

Reductant Injection - The urea or ammonia injection rate must be changed to match the NOx production rate. Too little reductant means that some NOx escapes unreacted, and too much results in significant ammonia emission in the exhaust, called "slip". As the catalyst efficiency increases or decreases due to temperature changes, reductant injection must be trimmed accordingly, complicating the control system. Controlling reductant feed rates is especially difficult during transients; the poor transient response of most present SCR systems makes SCR much less effective in highway vehicle use. However, SCR can be used on larger mobile sources such as ships and - in principle - locomotives, since these experience primarily steady-state operation. SCR systems have recently been installed on two diesel motorships operating into California, and the results have apparently been satisfactory (Albjerg & Morsing, 1990). SCR has also been installed in four low-powered (600 HP) diesel tunnel track maintenance machines in Switzerland, with what have been described by the vendor as excellent results (Offshore, 1989) (Environmental Emissions Systems, Inc., 1991). SCR has not yet been tried on a US high-power road locomotive, which would pose greater engineering demands.

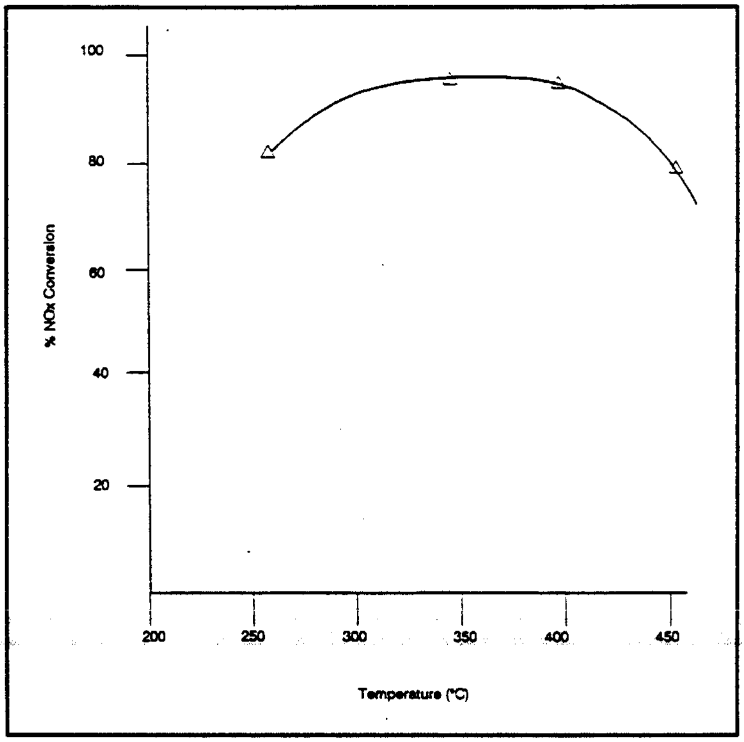

Figure 11: Catalyst efficiency vs. temperature.

atest SCR achievements - The Danish company Technik Thermische Maschinen (TTM) has been developing SCR in mobile applications for over 10 years. In early 1992 they successfully installed a catalytic converter system on a 2.4 MW (3200 HP) diesel ferry, using urea as the reductant. Over a combined steady-state and part-load duty cycle (average 37.1 % load), with extreme load change rates, the open-loop system reportedly achieves 95% NO reduction at less than 2 ppm ammonia slip (Hug, et. al., 1992). After 6000 hours of service, there has been no detectable degradation of performance, no soot or ash deposition, and no mechanical breakdowns. TTM researchers have developed an advanced concept catalyst design, which combines the ferry's system and other technologies in one package. Key features of this design are the following: 1) the cell geometry is modified (at some increase in backpressure) to increase the mass transfer and allow reduction in reactor size, 2) a separate adjoining reactor and bypass system is created, which uses amorphous chromia instead of vanadia/titania, allowing de-NOx at temperatures between 100 and 200 °C, and 3) the system would use a deep-bed particulate trap made from knitted ceramic fibers, now being investigated by the Swiss National Energy Research Foundation.

Conversion and operation issues - The operating environment and process constraints for SCR systems are more stringent in mobile systems than in the existing stationary SCR applications. Pressure drop limits, space requirements, outlet temperature, ammonia or ·'rea storage capacity, exhaust particulate content, vibration, weight, and ammonia slip would be concerns in a locomotive system design. Of these, the space requirement may be the most significant. The catalyst volume required to treat the exhaust from a locomotive diesel engine would be between eighty and ninety cubic feet (Bittner, 1992), not including the static assembly that transitions from the 2.5 square foot exhaust stack to the 16 square foot catalyst. A single unit of this volume is not available within the carbodies of most fully-equipped road locomotives as configured. One practical solution to this problem would be to raise the height of the locomotive hood to provide the extra space. The present height of most locomotives (about 15 feet), is considerably less than that of many of the cars they pull (for example, double-stack container cars at 20.25 feet; see Section 2.5), thereby presenting an SCR packaging opportunity.

Table 26: Exhaust temperatures by notch (°F).

Throttle Notch	EMD SD40-2 with 16-645E3	GE B39-8 with 16-7FDL
off		
brake	232.0	n/a
idle	194.9	271.0
1	259.1	524.7
2	350.1	798.3
3	436.7	878.0
4	518.7	810.7
5	605.9	782.0
6	681.8	755.0
7	713.2	757.3
8	740.9	754.3

On western US mainlines, there is generally considerable clearance above the locomotive, which could be used to accommodate parts of the SCR system. In taking advantage of this space, it must be kept in mind that the engineer's view must not be obscured, the fresh air path to the radiators must not be blocked, and the exhaust flow must remain unrestricted. It is not possible to occupy every foot of clearance with machinery, since air and exhaust must flow freely. EF&EE studied Railway Line Clearances, an industry publication that lists the permissible heights and corresponding widths of equipment on all the tracks of all the reporting railroads. We assumed a two foot height increase, to 17.5 feet, and a width for the SCR "box" of 8.4 feet (about 2 feet wider than the standard locomotive carbody). We then compared these requirements to the permissible widths listed in Railway Line Clearances to identify which existing routes would not permit use of locomotives having these dimensions.

Our review identified a number of track segments which could not accommodate an SCR-equipped locomotive having the dimensions outlined above, but only one of these segments is in an air basin of concern in California, and none of the others are on mainline routes serving California. Two tunnels between San Francisco and Bayshore, now used almost exclusively by the CalTrain commute service, restrict traffic to about 8 feet wide at 17.5 feet high, and might need to be widened slightly to accommodate the SCR system. Other restrictions on the SP network are on little-used lines. A segment from Echo to Ukiah, California is 7.3 feet wide at a height of 17.5 feet, but this is a line that sees less than 10 freight trains a week. A segment in the Cascade mountain range, from Hornbrook, California to Ashland, Oregon, is limited to 4.8 feet wide at its maximum (restricted) height of 17.25 feet. In Missouri there is a 150 - 200 mile spur that is restricted. Union Pacific has no restrictions at the 17.5 level. The Santa Fe tunnels in Franklin Canyon, in California's Bay Area, have recently been expanded to accommodate double-stacks, so no modifications are necessary. Santa Fe and Southern Pacific have recently finished expanding their Tehachapi, California tunnels for double-stacks.

Figure 12 is a partial cutaway view of a typical road locomotive (an EMD GP60). We have designed a concept SCR installation, and used this locomotive as a model. This was one of the more difficult installations identified. The engine is thoroughly surrounded by the turbocharger assembly, the dynamic brake unit, the carbody (outlined), and the auxiliary equipment stand. The space above the carbody is difficult to use because both the radiator and dynamic brake units need unrestricted flow at their tops and sides. The dynamic brake unit (or dynamic brake "hatch") is an autonomous, removable structure attached only by bolts and four electrical cables, and it is possible to raise it up and mount the catalytic reactor in its place. The exhaust silencer would not be needed, as the catalyst would fulfill its function.

The shape of our proposed reactor is a rectangular box 15 by 8.5 by 2 feet, centered in the locomotive and occupying 255 cubic feet. The reactor lies flat and sits directly over the engine, supported by the carbody (which may require stiffening with braces and other additional structure). A transition stack replaces the original stack and silencer and is bolted to the turbocharger housing and one end of the reactor. The exhaust flow exits the turbocharger, enters the transition where it is divided into left and right flows, which each enter side chambers along which are located multiple layers of catalyst blocks, either square blocks or cylindrical blocks, enough to make 41 cubic feet (minimum) total volume (total catalyst volume: 82 cubic feet). The flow leaving the catalyst layers empties into a single central chamber, at the top rear of which is the final exhaust stack. Additional volume is used by a blank catalyst layer (to accommodate a catalyst replacement program), transition blocks (flow modifiers), insulation, and catalyst supports.

In Figure 13, we have shown the same locomotive with the hypothetical reactor, represented as a shaded area, in place. The dynamic brake unit bolts to the reactor in the same way it originally bolted to the carbody. Aerodynamic fairings (not shown) could be added at each end of the dynamic brake unit to reduce air resistance. The exhaust stack protrudes through empty space at the middle end of the dynamic brake unit and rises high enough to place the plume above the dynamic brake cooling fan. The dynamic brake can be serviced without removing the entire unit.

A tank to hold the aqueous urea is fitted at the rear of the carbody, or another suitable location. It was assumed that reductant would be consumed only while operating in California. If 502 lbs of NOx are emitted each day, as might be the case for the most active line-haul locomotive, then about 500 pounds of solid urea would be required (1 lb solid urea per lb NOx). Then, 1700 pounds, or about 210 gallons, of aqueous urea would constitute a three day supply. The tank could be horizontal, but a vertical tank

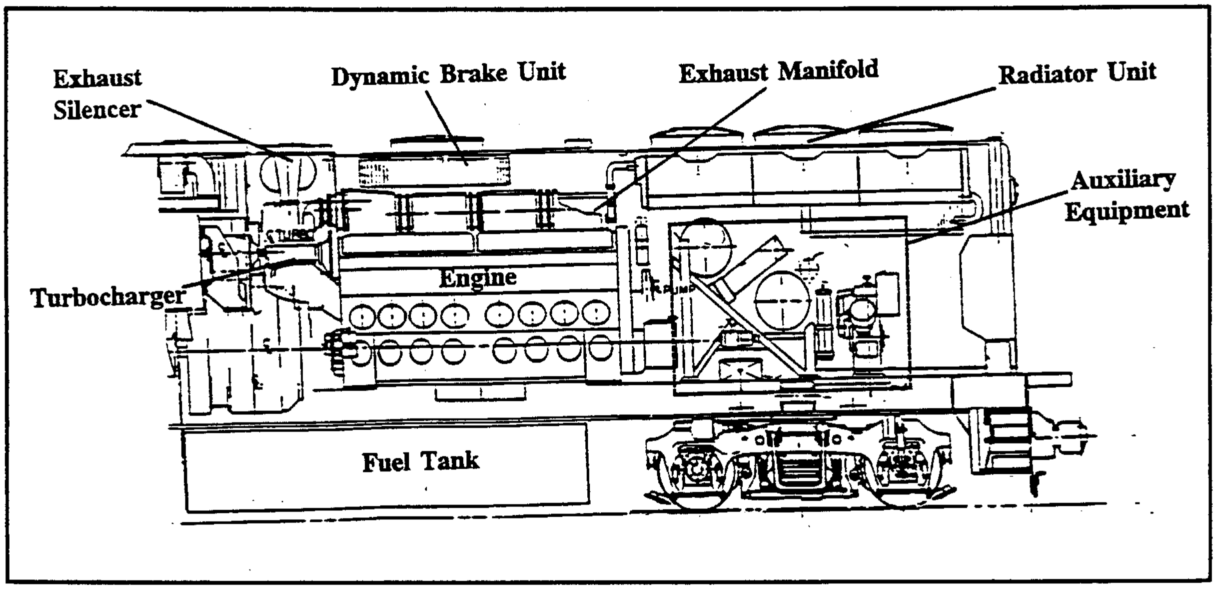

Figure 12: Cutaway indicating component location before SCR conversion.

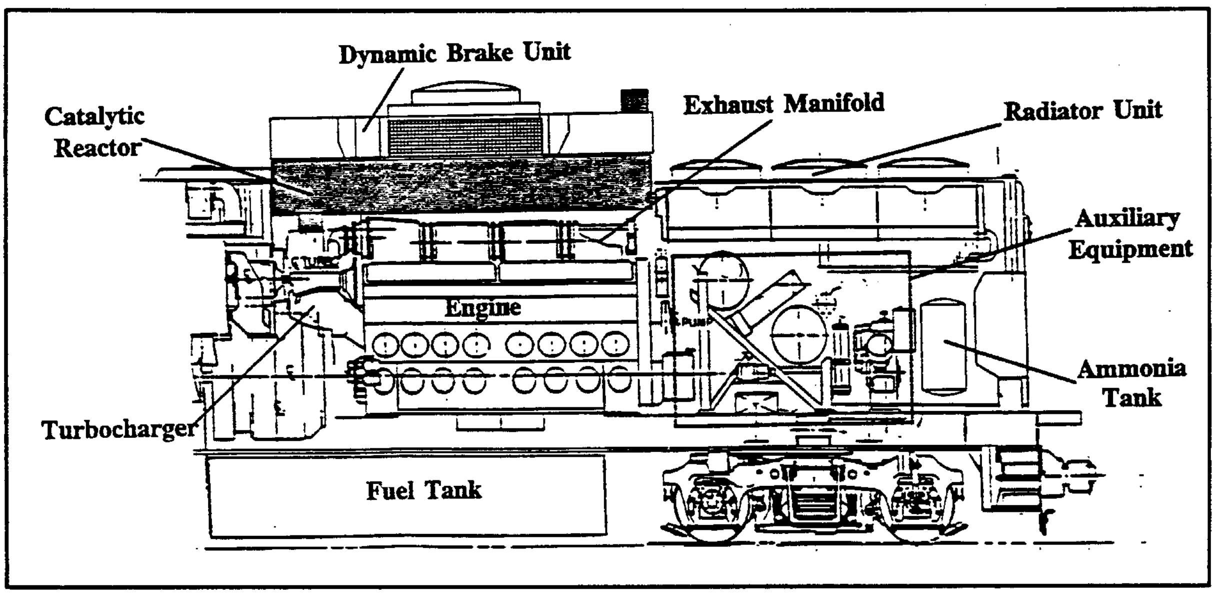

Figure 13: Cutaway indicating component location after SCR conversion.

would probably fit better in the limited space between the auxiliary equipment stand and the rear sand box. The urea tank would compete for space with the grease tank on wheel lubricator-equipped locomotives, and on a minority of locomotives there is not enough room at all behind the equipment stand for a single urea tank. A design using ammonia reductant might require a smaller tank (between 0.65 and 1 lb liquid ammonia per lb NOx). It would also be possible to divide the supply into two or more tanks for greater ease in packaging.

Other locomotive models could be modified similarly as shown in Figures 12 and 13. The GP38-2 and SD40-2 have dynamic brakes of similar size and in the same location as the GP-60, and so could use the same installation. The GE B38-2 has no large equipment above the engine, simplifying the installation. The same reactor unit, turned 180 degrees to line up with the exhaust stack, could be installed in the GE. If any of the conversions required greater reactor volumes or larger transition sections, the reactor height could be increased, or the radiator unit could be raised and a longer reactor installed. The radiator hatch is also an autonomous unit, but with complex plumbing rather than wires connecting it to the rest of the locomotive. The F40PH passenger locomotive conversion would be similar to the GP38-2 conversion, except that there may be a little less fore-and-aft space for the reactor. The F40 dynamic brake unit is likewise an autonomous structure bolted to the carbody.

A locomotive modified as suggested above may not fit though the doors of some locomotive repair shops and wash racks in California. The Southern Pacific Taylor Yard and Roseville Yard door openings are 18.25 feet (Harstad, 1992). We do not consider this a serious problem, since the existing clearance should be sufficient for the suggested design, the shops and washracks are easily modified structures, and at least one of the shops is scheduled for closing anyway.

Another potential objection to adding SCR is the additional weight it would impose on the axles and hence the track. However, this weight increase would not be substantial. A vendor estimated that the catalyst, insulation, inlet and outlet connections, support structure, and auxiliary equipment would weigh around 4 tons, which is a small fraction of the locomotive's total weight (160 to 200 tons). The small increase in axle load would exact some price in accelerated rail and roadbed wear and other costs. Four-axle locomotives cannot tolerate much more weight without exceeding presently allowable axle loading, but research has been proceeding for some time on higher axle loads. Further, as we suggested in Chapter 4, railroads will most likely choose to retrofit six-axle SD40-2 models for California service, rather than late-model, high-efficiency four-axle units. The SD40-2 locomotives carry a great deal of ballast to increase their tractive effort, and a reduction in this ballast loading could compensate for the weight increase due to the SCR unit.

Mounting over the engine is by no means the only way to package the SCR unit. Another alternative would be to mount the SCR system (possibly for an entire locomotive consist) in a separate tender or "SCR car", with locomotive exhaust ducted to it. This would have the advantage that the tender could be connected and disconnected as trains entered or left California, and that one tender could conceivably handle the exhaust of several locomotives. Calculations show that heat loss in a metal, insulated conduit (from the locomotive to the tender car) would not be prohibitive, but the many mechanical design issues of such a system could pose significant, and in our view, unreasonable, obstacles. Still another alternative would be to eliminate the crew cab of the converted locomotive. This would leave ample room for the reactor chamber and supporting equipment, but of course would eliminate space for crew. In yards, converted locomotives would have to be moved with other locomotives, or perhaps they could have simplified controls mounted on a panel accessible from the walkway. Cab-less units are already in use on major railroads, but they are rare since they have much less versatility than cab locomotives, and we believe that this lack of versatility (and hence poor utilization) dooms this approach. A third possibility is to mount the SCR unit on top of the locomotive *in front of* the exhaust stack. This space could easily accommodate a 3 x 3 x 15 foot box, which would provide ample space for both catalyst and transition volumes. Unfortunately, it would also have higher flow resistance and therefore higher backpressure than the design we described above. It could also possibly interfere with the air conditioning unit. These are problems that could be solved with some effort.

Other potential problems with SCR in locomotives include obtaining adequate reductant distribution in the exhaust stream, and achieving adequate control of the reductant feed rate. These two factors both affect conversion efficiency and ammonia slip. The SCR manufacturer's control strategy is to combine microprocessor control with a flow meter and a NOx analyzer in the exhaust stream, allowing mass balancing to ensure that the correct molar concentrations of ammonia and NOx are being reacted. It is also possible and less costly to operate "open loop", to inject urea (or ammonia) according to predetermined values related to speed, load, and exhaust temperature (Walker, 1992; Hug, et. al., 1992). This latter approach could fairly readily be integrated with the computer control of other engine functions found on late-model locomotives.

Since the locomotives proposed for retrofit do not produce sufficient exhaust temperatures for SCR below notch 4, it is desirable to investigate benefits of artificially increasing the temperature in those modes. The two diesel motorships mentioned above do so with electric heating coils mounted in the reactor chamber, at the expense of high energy consumption. Since locomotive diesels operate with great quantities of excess air, some 300 times more than they need for idle combustion, the exhaust temperatures could be increased by simply restricting the intake air at light loads. Since the air mass would decrease while the combustion energy stayed the same, the temperature of the air mass would go up. This is the method used by Detroit Diesel to increase idle combustion temperatures in its methanol DI engines. Rather than throttle the incoming air on these two-stroke methanol-diesel engines, DDC "recycles" it by bypassing the scavenge blower at low loads. A similar technique could be applied to EMD two-stroke engines. Figure 14, taken from a Pielstick air-fuel ratio controller design, indicates how such a device might be configured. Our calculations indicate that at idle one-sixth of normal intake flow would achieve the minimum temperature of 300 °C (572 °F). There is an additional benefit — "internal" exhaust gas recirculation, which has the effect of reducing the flame temperature, thus reducing NOx production in the engine.

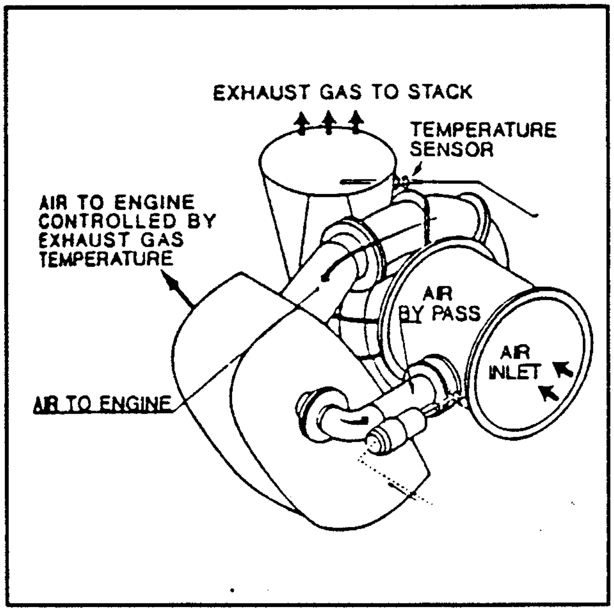

Figure 14: Turbocharger bypass.

There is a design choice of anhydrous ammonia, aqueous ammonia, or urea (solution of 60% water and 40% solid urea). For locomotives, it would be best to use aqueous (about 25% ammonia and 75% water) ammonia or aqueous urea, as anhydrous ammonia is a poison and fire hazard, and must be handled with great care. A tank of aqueous urea is relatively safe, and since it would only be needed within California, would adequately supply locomotives between refuelings. However, there would be some concern about freezing in the long mountain passes found in California.

Ammonia slip depends on the desired degree of NOx reduction, the size of the catalyst reactor, and how efficiently the reactor mixes available combustion products with available reductant. To increase the NOx reduction effectiveness, the urea input can be increased to a point, beyond which the ammonia slip goes up dramatically. Beyond this point, only an increase in catalyst volume can reduce NOx further. Ammonia slip of 5 - 10 ppm over the life of the catalyst, considered acceptable for stationary applications, has been demonstrated on mobile applications such as the two diesel motorships (Albjerg & Morsing, 1990).

To aid in proper mixing in the exhaust stream, multiple nozzles prior to the exhaust reactor could be employed to distribute urea throughout the exhaust. It would also be possible to inject the urea solution ahead of the turbocharger, which would ensure adequate mixing. Locomotive engine manufacturers have stated that turbocharger materials would not be harmed by such a design, as long as the turbo temperatures remain below reasonable levels (Brann, 1992).

9.2 Costs and Cost-effectiveness

Emission calculations - In order to calculate the emission reduction due to SCR, it was first necessary to predict the effectiveness of the SCR system over a representative locomotive duty cycle. Typical exhaust temperatures are known, and SCR system models for EMD and GE locomotives were supplied by a catalyst manufacturer (Bittner, 1992). A base metal catalyst of forty-one cubic feet (Bittner, 1992), should be able to convert NOx to N_2 and O_2 at 90% maximum efficiency between 300 and 375 °C, and at lesser efficiencies according to a curve like that of Figure 11. Our calculations reduce the baseline NOx in this way. Table 27 shows the NOx reduction efficiency in each throttle notch without air restriction to increase exhaust temperature at low power. The same data analyzed with air restriction indicates 89% NOx reduction efficiency. The locomotive used for the calculations is an EMD SD40-2, which we expect to be the major type of locomotive to be converted. Next is a column showing the weighted (untreated) NOx emission, in pounds per hour, based on measured emission factors (Conlon, 1988) and weighted by the fraction of time spent in each notch over the duty cycle. The NOx emission with SCR is then calculated by reducing the baseline NOx by the predicted catalyst efficiency. The sums of each of these two columns, multiplied by hours in a day and days in a year and divided by 2000 pounds per ton, is the total NOx in tons per year.

Table 27: Throttle profile & NOx emissions, no exhaust heating, EMD SD40-2, line-haul cycle.

Throttle Notch	SCR NOx Efficiency	Baseline Weighted NOx (lb/hr)	NOx, with SCR (lb/hr)
off		0.00	0.00
brake	-	0.51	0.51
idle	-	1.22	1.22
1	-	0.22	0.22
2	-	0.34	0.34
3	-	0.56	0.56
4	0.80	0.92	0.18
5	0.90	1.08	0.11
6	0.90	1.24	0.12
7	0.90	1.42	0.14
8	0.90	7.57	0.76
Total (lbs/hr)		15.1	4.2
Total (tons/yr)		58.1	16.0
NOx reduction (tons)			42.1
Percent reduction			72%

From these calculations, we estimate that SCR without exhaust heating would reduce NOx emission from the SD40-2 by 72% over the line-haul duty cycle. With the addition of air restriction at light loads to heat the exhaust, the projected efficiency increases to 89%. Analysis for the other three locomotive models considered gave similar results, although the impact of exhaust heating is even larger for the lightly-loaded switcher and local duty cycles. The resulting emission reductions (assuming exhaust heating) were calculated and used in the cost-effectiveness analysis.

Conversion Costs - The cost of an SCR system has been estimated at $75,000 plus $75 per horsepower for a base-metal catalyst unit, based on vender cost estimates. This includes the reactor unit itself, with catalyst, a tank for the urea with supporting structure and plumbing, a control unit with sensors and actuators, and modifications to the turbocharger and intake system for air bypass. An additional $25,000 ($10,000 for switchers) was added to this sum for modifications to the locomotive to raise the hood, mount the reactor, and remount the dynamic brake, if so equipped (EF&EE estimate). The sum totals of these costs appear in the first lines of Table 28 and Table 29.

Operating and Maintenance Costs - The SCR reactor would be filled with catalyst layers (rectangular or cylindrical blocks of metal substrate, coated with the catalytic materials), held in place by an insulating lattice of glass or composite fibers. An effective SCR system, whether mobile or stationary, requires routine replacement of these catalyst blocks (for example, complete catalyst replacement every 4 years). The catalyst shows its age by losing conversion efficiency in a linear decline, until the catalyst is no longer able to meet design minimums. It is most economic to replace (or add) layers of blocks at a time. A catalyst vendor has predicted $6.50 per horsepower annual maintenance cost on the line-haul application, including replacement and cleaning of catalyst material and all labor (Morsing, 1992). Our analysis uses that figure for line-haul locomotives, that figure less 10% for locals and that figure less 20% for switchers (Wagner, 1992). Although we have used current dollars to substitute for future dollars, we expect higher production volumes and recycling to keep the prices down.

Cost effective-ness - The system was assumed to be a maximum 90% effective (i.e, it follows the SCR efficiency schedule of the "with exhaust heating" case), and to consume one lb solid urea per pound of NOx removed.

Table 28: Cost-effectiveness of SCR for line-haul locomotives.

	EMD GP60		GE B39-8		EMD SD40-2	
	Line-haul cycle		Line-haul cycle		Line-haul cycle	
	Baseline	With SCR	Baseline	With SCR	Baseline	With SCR
Capital cost ($)		$396,250		$392,500		$325,000
Useful life (yrs)		10		10		10
Annualized cost ($/yr)		$59,053		$58,494		$48,435
NOx emiss. (t/yr)	80.0	8.6	81.3	10.3	58.1	6.2
Urea cons. (t/yr)		71.4		71.0		52.0
Urea price ($/ton)		$350		$350		$350
Urea cost ($/yr)		$25,007		$24,842		$18,183
Fuel penalty ($/yr)		$6,247		$16,481		$5,448
Maintenance ($/yr)		$25,675		$25,350		$17,550
Total cost ($/yr)		$115,982		$125,166		$89,616
Cost effectiveness ($/ton)		$1,623		$1,763		$1,725

The urea is priced at $350 per ton, which assumes fairly large lots delivered by a vendor (Bock, 1993). Ammonia is approximately $250 per ton. Fuel consumption would increase slightly due to the higher exhaust backpressure and the extra air resistance created by taller line-haul locomotives. This increase was estimated (probably conservatively) at 3%. Another 5% in fuel consumption was added to the GE engine in idle through notch 3 to reflect throttling losses (blower bypass on the EMD engines would not impose similar losses). The useful life of the SCR system (other than the catalyst) was assumed to be 20 years, or 10 years for the severe conditions of line-haul service. As Table 28 shows - given these assumptions - SCR could be a cost-effective measure for line-haul locomotive emission control, at about $1,600 per ton on an EMD GP60, $1,800 per ton on a GE B39-8, and $1,700 per ton on an EMD SD40-2.

As for the light duty locomotive cycles, shown in Table 29, the cost per ton increases significantly. For the SD40-2 in local service, the cost-effectiveness of SCR is calculated at $2,800 per ton, and for the GP38-2 in switcher service at $2,900 per ton. These costs are still very attractive compared to the costs of controlling NOx from stationary sources and many mobile sources.

With exhaust heating and sufficient reactor size it appears entirely possible to remove 90% of the engine's NOx, with less than 10 ppm NH_3 slip. The reactor size is the likely limiter, since its size depends greatly on how well the exhaust stream can be fed through the catalyst blocks without unduly raising backpressure. A lower-effectiveness scenario can be imagined where the reactor must be much smaller due to packaging constraints or some other reason. As a sensitivity check, the cost-effectiveness was recalculated with a maximum catalyst efficiency of 70%, and the SCR was turned off below Notch 4. The resulting numbers were $2,400, $2,900, $2,000, $5,500, and $8,800 for the three line-haul, the local, and the switcher locomotives, respectively. At these levels SCR would still be an attractive line-haul NOx control measure, but would be only marginally cost-effective for locals and switchers.

It is likely that SCR conversion costs would come down significantly once the units are produced in quantity and greater experience is gained. For a higher-effectiveness scenario, the conversion costs were reduced to $50 per hp and $50,000 flat (other costs the same), and maintenance was decreased to $5.50 per hp. The resulting numbers were $1,300, $1,600, $1,000, $2,100, and $2,700 for the three line-haul, the local, and the switcher locomotives, respectively. These figures show how, despite the high initial cost, SCR could be a reasonable measure for reducing NOx.

Table 29: Cost-effectiveness of SCR for local and switch locomotives.

	EMD SD40-2		EMD GP38	
	Local cycle		Switcher cycle	
	Baseline	With SCR	Baseline	With SCR
Capital cost ($)		$325,000		$235,000
Useful life (yrs)		20		20
Annualized cost ($/yr)		$33,102		$23,935
NOx emiss. (t/yr)	24.0	2.6	15.9	2.1
Urea cons. (t/yr)		21.4		13.8
Urea price ($/ton)		$350		$350
Urea cost ($/yr)		$7,491		$4,823
Fuel penalty ($/yr)		$2,187		$1,120
Maintenance ($/yr)		$17,550		$10,400
Total cost ($/yr)		$60,330		$40,278
Cost effectiveness ($/ton)		**$2,819**		**$2,923**

9.3 Regulatory Feasibility

A requirement to implement SCR would pose no unusual problems from a regulatory/enforcement perspective. Regulations would presumably be phrased in terms of performance, and railroads would be required to provide test data for each unit to verify proper operation. ARB inspectors could then spot-check occasionally to verify that the units were functioning.

9.4 Affordability

In all of California, we estimate that conversion of all the line-haul, local, switcher, and passenger locomotives to SCR would cost about 360 million dollars (see discussion of number of locomotives in Chapter 4). This is the up-front capital cost only, in current dollars, and does not include fuel penalties or costs of supplying reductant. We assumed that all of Amtrak's California assigned locomotives would be converted, as well as the CalTrain and Metrolink rosters. Based on the recent announcement of several locomotive orders at total costs higher than this, this cost is likely within the railroads' financial capabilities.

9.5 Impact On Railroad Operations

If SCR were implemented only in California, this would require setting up a California-only locomotive fleet, with changes of locomotives required at gateway points. The costs and operational impacts would be significant, as discussed earlier, but not insurmountable. An alternative would be to equip a larger number of units, and to use these on the major runs into and out of California (SCR would only have to be turned on in California).

If SCR were implemented by raising the roof line of the locomotives, this might limit their ability to use certain shops, wash racks, and other facilities, and some isolated branch lines. These limitations are not expected to be significant; as we stated above, clearances are generous and shop facilities are easily modified. No mainlines in California or adjacent states were found to have limiting overhead clearance, and large line-haul locomotives are prevented from entering many branchlines anyway due to tight curves.

9.6 Implementation Schedule

Conceptually, the installation of SCR on locomotives is straightforward, as we have demonstrated, but there is no practical experience to build on, and there are some unanswered questions. The two diesel motorships contribute little to the experience because their designers had so much space to work with, and because cost was a secondary concern[30]; the Swiss track grinder designers had a tight package but only 600 hp to clean up. Nonetheless, SCR retrofit requirements are simple enough that locomotive rebuilders, working with designs from catalyst manufacturers, could easily perform the work. Morrison-Knudsen is setting an example by building dedicated natural gas locomotives, using Caterpillar-designed engines, for the emerging low-emission locomotive market. These locomotives have progressed from deal to saleable product in less than two years.

"Saleable product" may mean something different for SCR, though. It will be easy to place a reactor on board and make it work; it will be a much greater challenge to make it survive the extreme vibration and resultant G-forces typical of a locomotive environment. Also, the additional heat in the carbody produced by an SCR reactor, insulated or not, could require other design changes. The cleaning and regeneration of catalysts that have been fouled by bad turbochargers and stuck injectors would have to be investigated. Poisons in the lube oil would be of concern. Therefore, we would expect a greater lead-time (than for natural gas or other measures) for SCR to become a useable product (Gladden, 1992).

Unlike alternative fuels and electrification, the Selective Catalytic Reduction scenario needs little infrastructure building, assuming that reductant suppliers will take care of all production and most inventory responsibilities. Urea tanks and dispensers would be placed alongside fuel dispensers at existing railroad fueling depots. Locomotive heights would not be increased so as to make tunnel or bridge modifications necessary. Also in SCR's favor, a broken SCR unit does not *likely* mean a dead locomotive. Converted locomotives could operate freely at maximum capacity with broken SCR units, so that SCR should not have a significant effect on service reliability. Possible exceptions would be locomotives with SCR units incapacitated by over-fueling (too much fuel in the combustion chambers) or turbocharger failure, which could so clog the catalyst blocks they no longer permit adequate exhaust flow. These faults would be likely to stop the engine anyway. This does not, of course, mean that routine operation with non-functioning emission control equipment would be tolerated, but only that the possibility of such operation in an emergency could limit the operational impacts of SCR.

Given the present state of SCR technology for diesel engines, a demonstration program for this technology in locomotives could be undertaken almost immediately. This would preferably be undertaken by a consortium of a locomotive rebuilder, a catalyst manufacturer, and one or more railroads. Since neither the major locomotive builders nor their customers, the railroads, have any incentive to demonstrate the feasibility of such a costly emission control technique, funding for this demonstration will probably need to come from public sources. Assuming that funds were budgeted for the next fiscal year, an RFP could be issued in Fall, 1995, and work could start around the beginning of 1996. Allowing two years for design and construction and two years of operation, such a demonstration would take about four years (i.e. the end of 2000) to yield results (although interim data would be available much sooner). These results could serve as the basis for converting a larger number of locomotives, beginning in 2001. Assuming that each of the major railroads converted 25 units in 2000, and 50 units each year thereafter, the California line-haul and local fleets could be completely converted to SCR by 2006.